

A THEORETICAL AND EXPERIMENTAL STUDY
OF NOISE AND DISTORTION
IN THE RECEPTION OF FM SIGNALS

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Abstract

A mathematical model is developed that can be used to analyze the effects of multipath on any modulation of an FM carrier. The predictions of this model are verified by simulation and by actual field testing. The model is used to analyze the existing FM stereo system and the proposed FMX system. The analysis, confirmed by field tests in over 15,000 locations, shows that FMX transmission significantly degrades reception on existing FM stereo receivers and that FMX receivers are inferior to FM stereo receivers for receiving FMX transmissions.

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1.0 Introduction

Since its inception in 1938 as a system for commercial broadcasting, FM has been recognized for its superior noise performance and fidelity over AM broadcasting. The fidelity results primarily from the extended audio bandwidth. The superior noise performance stems principally from the spread-spectrum (deviation ratio greater than unity) choice for the FM signal and from the use of pre-emphasis in the modulating signal.

As originally proposed and practiced, the audio modulating signal was limited to 15 kHz and the peak deviation was 75 kHz. The dynamic range and fidelity of this monaural system was and still is the reference standard for commercial broadcasting. The principal limitation of this system, as with all current and proposed commercial FM systems, is, as we shall see, caused by multipath which limits the performance of fixed as well as mobile receivers.

With the passage of time, engineers began looking at the frequency range from 15 to 75 kHz and beyond with an eye to using it for different purposes. In some cases it was even regarded as unused “free” frequency space which was available without requiring additional transmitter power and without any, or at least any clearly understood, penalties. In 1961 stereo was introduced using the space between 23 and 53 kHz. And today we have additional signals such as SCA, ARI, RDS and the proposed FMX system, all of which add spectral components beyond 15 kHz.

2.0 Objectives

It was an objective of the research reported in this paper to develop a mathematical model that can be used to analyze and assess the effects of multipath on any existing or proposed modulation of an FM carrier. It was a further objective to simulate the system for the dual purposes of verifying predictions of the model and correlating observations with those made in actual field tests. Finally, as an example, we will compare two systems of current interest – the existing FM stereo system and the proposed FMX system.

3.0 The Multipath Model

As the name suggests, the model of the medium is that of more than one path traversed by the transmitted signal on its way to the receiver. While we have examined up to six paths, we shall present here only the analysis for two paths because, with but one exception, this model is capable of explaining all of our field observations.

And the one exception is easily handled by inspection through the addition of a very simple third path to the two-path model.

The multipath system model that we will analyze is shown in Fig. 1. In this figure we include in the magnitude of the reflection coefficient the differential attenuation due to the longer path traversed by the reflected signal compared to that of the direct signal. (It should be noted that the notation of “direct” and “reflected” paths, while conveniently descriptive, is not always appropriate. In some situations there may be no direct signal but two reflected signals seen by the receiving antenna. In such cases the model of Fig. 1 is still applicable by simply normalizing to unity gain on the path having the greater gain and allowing T_1 to be greater than T_2 if necessary.)

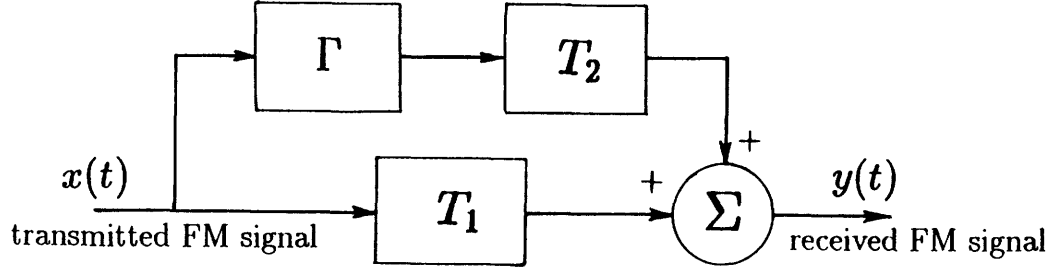


Figure 1: Multipath system model. T_1 = delay of direct path; T_2 = delay of reflected path. Γ = reflection coefficient = $|\Gamma|e^{j\phi}$ where $|\Gamma| \leq 1$. $x(t)$ is the transmitted signal and has the form: $x(t) = \cos[\omega_0 t + \alpha \int_0^t m(\tau) d\tau]$, where ω_0 = carrier radian frequency, α = maximum deviation radian frequency, and $m(\tau)$ = normalized audio modulating signal obeying the condition $|m(\tau)| \leq 1$.

3.1 Derivation of Error Due to Multipath

We can represent the transmitted FM signal in terms of complex exponentials as

$$x(t) = \text{Re}\{e^{j[\omega_0 t + \alpha \int_0^t m(\tau) d\tau]}\} \quad (1)$$

With this signal as the input to the system of Fig. 1 we have the output

$$y(t) = \text{Re}\{e^{j[\omega_0(t-T_1) + \alpha \int_0^{t-T_1} m(\tau) d\tau]} + |\Gamma|e^{j\phi} e^{j[\omega_0(t-T_2) + \alpha \int_0^{t-T_2} m(\tau) d\tau]}\} \quad (2)$$

Factoring out the first term we obtain

$$y(t) = \text{Re}\{ \underbrace{e^{j[\omega_0(t-T_1) + \alpha \int_0^{t-T_1} m(\tau) d\tau]}}_{\text{transmitted signal delayed by } T_1} [1 + |\Gamma|e^{j[\phi - \omega_0(T_2-T_1) - \alpha \int_{t-T_2}^{t-T_1} m(\tau) d\tau}]] \} \quad (3)$$

Since a pure time translation of the output signal has no effect upon errors between the transmitted and received signals we will look at $y(t + T_1)$ instead of $y(t)$ as this will simplify some expressions and interpretations that follow.

$$y(t + T_1) = \text{Re}\{e^{j[\omega_0 t + \alpha \int_0^t m(\tau) d\tau]} [1 + |\Gamma| e^{j[\phi - \omega_0(T_2 - T_1) - \alpha \int_{t-(T_2 - T_1)}^t m(\tau) d\tau]}\}\} \quad (4)$$

The first factor in equation (4) represents the transmitted signal, as can be seen from equation (1). It is a vector in the complex plane with unity magnitude that is rotating with exactly the instantaneous frequency of the transmitted signal. In the absence of multipath, i.e. $|\Gamma| = 0$, equation (4) shows that the received signal is a replica of the transmitted signal with no distortion. The factor in the large square brackets of equation (4) provides the key to the distortion that is caused by multipath. The magnitude of this factor gives the instantaneous AM that is generated by the multipath process and the rate of change of the angle of the factor gives the additive error in the instantaneous frequency caused by the multipath.

Let's look first at the integral in this second factor of equation (4). The integral is equal to the output of a linear filter whose impulse response, $h(t)$, is shown in Fig. 2 and whose input is the modulating signal $m(t)$. The transfer function, $H(\omega)$, that belongs to the filter with the impulse response $h(t)$ is then

$$H(\omega) = (T_2 - T_1) \frac{\sin \frac{\omega(T_2 - T_1)}{2}}{\frac{\omega(T_2 - T_1)}{2}} e^{-j\frac{\omega}{2}(T_2 - T_1)} \quad (5)$$

From this equation it is seen that this filter is a $\frac{\sin x}{x}$ type filter with a linear phase shift corresponding to a delay of $\frac{T_2 - T_1}{2}$ seconds. If we let

$$G(\omega) = \frac{H(\omega)}{T_2 - T_1} \quad , \quad (6)$$

then the magnitude $|G(\omega)|$ is as shown in Fig. 3. Note that the first zero of the $\frac{\sin x}{x}$ function occurs at $\frac{1}{T_2 - T_1}$. For a difference in the two path lengths of 2 km, this first zero occurs at 150 kHz. Thus for path length differences of less than 2 km, $G(f)$ has essentially no effect on $m(t)$. If we let $\widehat{m}(t)$ be the output of the filter $G(f)$ with input $m(t)$, we can write

$$\alpha \int_{t-(T_2 - T_1)}^t m(\tau) d\tau = \alpha \cdot (T_2 - T_1) \cdot \widehat{m}(t) \quad (7)$$

in which $\widehat{m}(t)$ can be replaced by $m(t)$ for path length differences of less than 2 km and for path length differences greater than this, $\widehat{m}(t)$ is progressively a low-pass filtered version of $m(t)$.

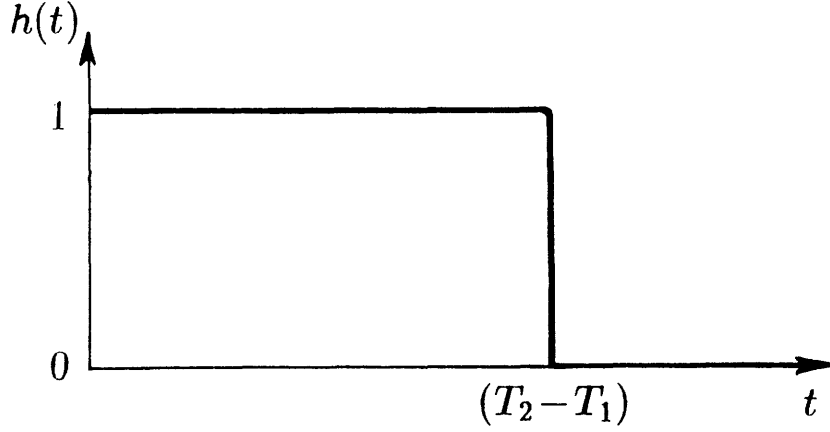


Figure 2: Impulse response of a filter acting on $m(t)$ to yield an output equal to $\int_{t-(T_2-T_1)}^t m(\tau) d\tau$.

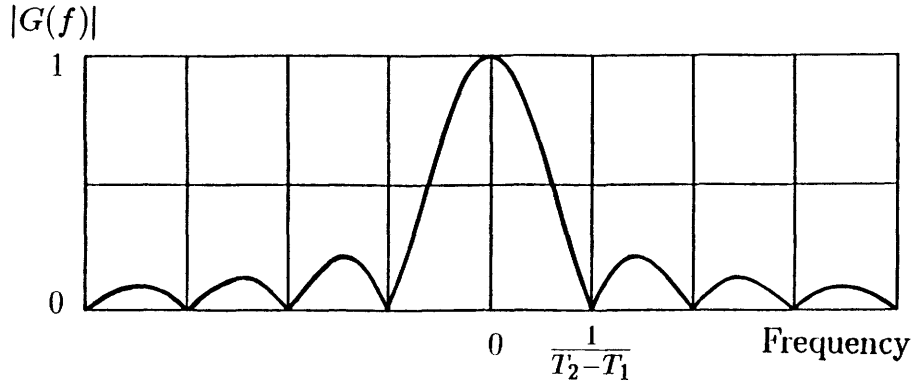


Figure 3: Magnitude of transfer function $|G(f)|$.

Now using equation (7) in equation (4), we can construct a vector diagram in the complex plane for the factor that is in the large square brackets of equation (4). This vector diagram is shown in Fig. 4 and is very useful in understanding the effects of multipath for any modulating functions $m(t)$ and therefore can be applied to analyze all existing systems as well as proposed systems.

The angle $\theta_D(t)$ in Fig. 4 is the angle of the second term in the large square brackets of equation (4). It is

$$\theta_D(t) = \phi - \omega_0 (T_2 - T_1) - \alpha \cdot (T_2 - T_1) \cdot \widehat{m(t)} \quad (8)$$

which can be written in terms of the two path lengths D_1 and D_2 of the multipath system as

$$\theta_D(t) = \phi - \omega_0 \left(\frac{D_2 - D_1}{c} \right) - \alpha \cdot \left(\frac{D_2 - D_1}{c} \right) \cdot \widehat{m(t)} \quad (9)$$

in which c is the speed of light.

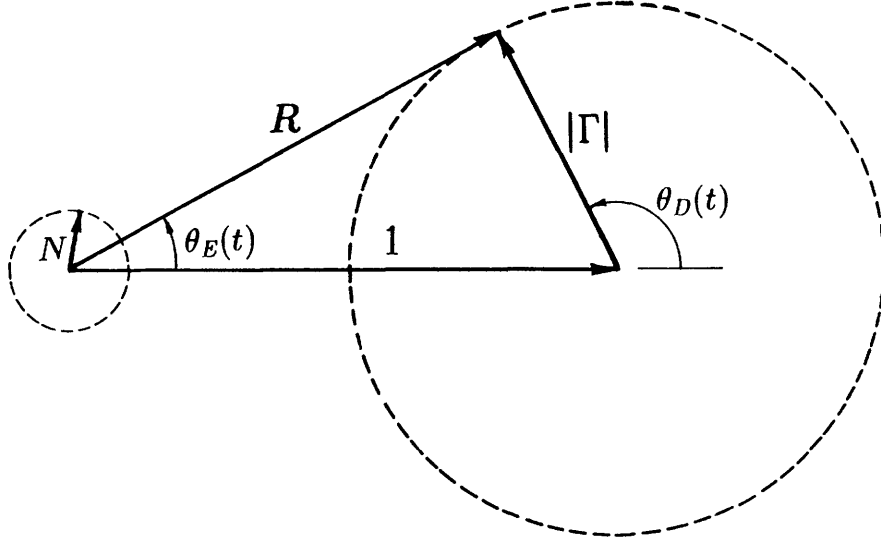


Figure 4: Vector diagram relating the instantaneous phase error, $\theta_E(t)$, and the magnitude R of the received signal to $\theta_D(t)$ and $|\Gamma|$ in which $\theta_D(t)$ is given by equation (9).

The angle $\theta_E(t)$ in Fig. 4 is the instantaneous additive phase error introduced by the multipath. The small circle of radius N in Fig. 4 represents the noise threshold for the system in the sense that if $|\Gamma|$ is large enough such that the tip of the received signal vector¹ R falls within this circle at any time the noise in the system output at that time will dominate the signal. The radius N is a function of the signal strength of the direct path, the noise generated in the receiver prior to the detector and the noise seen by the antenna.

If the two circles in Fig. 4 intersect then multipath will cause, in addition to distortion, bursts of noise that are modulation dependent. If the circles do not intersect the effect of multipath is pure distortion (i.e. an error signal that is correlated with the modulation). These results are readily seen from Fig. 4 in view of the expression for $\theta_D(t)$ given in equation (9). Even in the case of mobile receivers, D_2 and D_1 are slowly varying functions compared to $\widehat{m}(t)$ and therefore the first two terms in equation (9) can be considered to be constant relative to the third term which is directly proportional to $\widehat{m}(t)$. Thus it is $m(t)$ that drives the angle $\theta_D(t)$. The larger $m(t)$ is the larger are the variations in the instantaneous phase error $\theta_E(t)$.

In an FM receiver it is the instantaneous frequency error $\omega_E(t)$ rather than the instantaneous phase error $\theta_E(t)$ that is of direct interest. From the geometry of Fig. 4 it is clear that we can solve for $\theta_E(t)$ in terms of $\theta_D(t)$ and $|\Gamma|$. This result is presented

¹Recall that the length of this vector represents the magnitude of the second factor in equation (4) and therefore represents the normalized magnitude of the received signal in the model.

later in equation (19). However, for the moment we can develop more insight into the multipath problem if we simply represent the relationship between $\theta_E(t)$ and $\theta_D(t)$ in the functional form

$$\theta_E(t) = F(\theta_D, |\Gamma|) \quad . \quad (10)$$

From this we can obtain the instantaneous frequency error $\omega_E(t)$ directly in the form

$$\omega_E(t) = \frac{d\theta_E(t)}{dt} \approx \frac{\partial F(\theta_D, |\Gamma|)}{\partial \theta_D} \cdot \frac{d\theta_D(t)}{dt} \quad (11)$$

in which we have made use of the fact that the variation in $|\Gamma|$ is very slow compared to that of $\theta_D(t)$.

Using equation (9), with the knowledge of the slowly varying D_1 and D_2 discussed earlier, we have

$$\omega_E(t) \approx -\alpha \frac{(D_2 - D_1)}{c} \cdot \frac{\partial F(\theta_D, |\Gamma|)}{\partial \theta_D} \cdot \frac{dm(t)}{dt} \quad . \quad (12)$$

This equation shows the important result that the instantaneous frequency error at the output of the receiver detector is directly proportional to the derivative of the modulation – independent of the composition of the modulating signal and therefore independent of the system used to FM modulate the carrier.

3.2 Observations from Examination of the Frequency Error

1. The effect of the addition of spectral components to $m(t)$ in the higher frequency range.

Equation (12) clearly shows that the addition of any spectral components to $m(t)$ in the higher frequency range increases the error in the receiver output. This is why, for example, FM stereo broadcasts have more problems with multipath than do FM monaural broadcasts. It is also why systems which add subcarriers, such as SCA, and systems which add spectral components in the 23 to 53 kHz region, beyond those already present in FM stereo, as in the proposed FMX system, inherently result in higher distortion and greater signal-modulated noise. (For the spectral composition of FM and FMX modulation signals, see Figs. 8, 9 and 11.)

The magnitude of the penalty for adding high frequency spectral components to the modulating signal $m(t)$ is best appreciated by the following example: Consider a modulation $m(t)$ consisting of a sine wave at 1 kHz. If the

amplitude of this sine wave is held constant and its frequency is increased to 38 kHz then, from equation (12), the instantaneous error at the detector output caused by multipath rises by 31.6 dB!

2. The effect of AM modulated spectral components added to $m(t)$ above 15 kHz.

There is still more information to be extracted by inspection of equation (12). Namely, any spectral components that are added above 15 kHz with AM modulation at audio frequencies give rise to distortion components in the monaural signal range below 15 kHz. This follows from equation (12) by noting that $\frac{\partial F(\theta_D, |\Gamma|)}{\partial \theta_D}$ is a nonlinear function of θ_D and therefore, in view of equation (9), is a nonlinear function of $m(t)$. The product of the last two factors in equation (12) therefore provides the nonlinear terms necessary to produce base-band distortion components from AM modulated signals above the audio band. Thus monaural reception of a stereo broadcast incurs more multipath distortion than monaural reception of a monaural broadcast. Similarly, reception of an FMX broadcast results in more multipath distortion in the monaural (L+R) base-band than would result from an FM stereo broadcast whenever the compressed (L-R) signal of FMX is a significant addition to the normal stereo (L-R) signal – that is whenever the FMX signal has the possibility of reducing background noise. The quantitative aspects of this are presented later in section 4.5.

3. The effect of $(D_2 - D_1)$ on multipath generated distortion.

Finally, equation (12) contains interesting information about the effect of the difference $(D_2 - D_1)$ in path lengths upon the multipath generated distortion. We see that this distortion is proportional to the difference in the path lengths. If we compute $\omega_E(t)$ as we do in the material that follows, we find that the distortion is insignificant for $D_2 - D_1 = 10$ meters and very significant for $D_2 - D_1 = 1000$ meters, depending upon $|\Gamma|$. It is tempting to say that for large $D_2 - D_1$ the distortion will be negligible because $|\Gamma|$ (which remember includes the differential attenuation of the two waves due to different distances travelled) will be small. However there are many situations involving shadowing of the direct wave in which severe multipath distortion ($|\Gamma|$ close to unity) can occur with very large differences in the path lengths. This is particularly common in rural hilly areas.

3.3 The Generation of Quadrature Modulation Signals by Multipath

The general case of this phenomenon can be seen from equation (12). The generation of quadrature modulation signals is a direct consequence of the fact that the additive error signal at the output of the receiver detector, $\omega_E(t)$, is proportional to $\frac{d\widehat{m}(t)}{dt}$ as shown in equation (12). Thus the additive error signal contains spectral components that are shifted 90° from those contained in the original modulation, and the magnitude of the quadrature error components is proportional to the frequency of the corresponding component in $m(t)$. This can be illustrated and understood very clearly for the special, yet very practical, case in which the product of $(D_2 - D_1)\widehat{m}(t)$ in equation (9) is sufficiently small such that the excursion of $\theta_D(t)$ in Fig. 5 is small enough to justify a linear analysis. We shall examine the case in which we experience the strongest effects of multipath, namely when $\theta_D(t)$ is in the vicinity of π as indicated in Fig. 5. From equation (9), with the assumption of slowly varying D_2 and D_1 , we have

$$\frac{d\theta_D(t)}{dt} \approx -\alpha \frac{(D_2 - D_1)}{c} \cdot \frac{d}{dt}(\widehat{m}(t)) \quad (13)$$

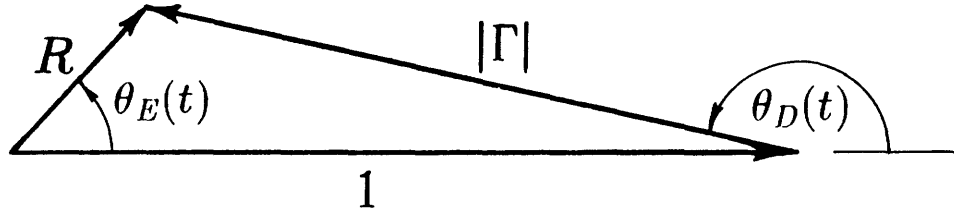


Figure 5: Vector diagram for $\theta_D(t) \approx \pi$.

We shall examine the phase error for $D_2 - D_1 = 1$ km. For this case we have seen that we can replace $\widehat{m}(t)$ by $m(t)$ and we have

$$\frac{d\theta_D(t)}{dt} \approx -\alpha \frac{(D_2 - D_1)}{c} \cdot \frac{dm(t)}{dt} \quad (14)$$

For $\theta_D \approx \pi$, $R \approx 1 - |\Gamma|$. Let $m(t) = A \cos(\omega_m t)$ in which $A \ll 1$. Then, from equation (14),

$$\frac{d\theta_D(t)}{dt} \approx \alpha A \frac{(D_2 - D_1)}{c} \omega_m \sin \omega_m t \quad (15)$$

And, from the vector diagram of Fig. 5 we have the relation

$$R \frac{d\theta_E}{dt} \approx -|\Gamma| \frac{d\theta_D(t)}{dt} \quad (16)$$

The error signal at the detector output is

$$\omega_E(t) = \frac{d\theta_E}{dt} \approx \frac{-|\Gamma|}{1 - |\Gamma|} \cdot \frac{d\theta_D(t)}{dt} = \frac{-|\Gamma|\alpha A\omega_m(D_2 - D_1)}{(1 - |\Gamma|)c} \sin \omega_m(t) \quad (17)$$

which is recognized as a signal in quadrature to the original transmitted signal. From equation (17) we see that, depending upon $|\Gamma|$, the multipath-generated quadrature signal can even have a much larger amplitude than the modulating signal that generates it. The fact that multipath generates quadrature components to the spectral components contained in $m(t)$ spotlights one of the principal flaws in the concept of the proposed FMX system. FMX adds compressed and frequency contoured quadrature components to the normal (L–R) modulating signals in the region of 23 to 53 kHz. By the time the multipath signals arrive at the receiving antenna, the original L–R and the compressed L–R quadrature signals are inextricably mixed. This degrades the performance of existing FM receivers when receiving FMX transmissions and, for reasons discussed in section 4.5, actually causes an FMX receiver to be inferior to an existing FM receiver for the reception of FMX transmissions in the presence of multipath. In the work that follows we shall refer to these multipath generated quadrature components as quadrature distortion components.

3.4 Effects of Multipath on Phasing Errors in the Decoding of the 38 kHz Subcarrier

In Fig. 6 we represent the complex amplitudes of the desired modulating signal and the multipath induced error from equation (17) as vectors in the complex plane. From the vector diagram shown in Fig. 6,

$$\eta = \tan^{-1} \left[\frac{|\Gamma|(D_2 - D_1)\omega_m}{(1 - |\Gamma|)c} \right] \quad , \quad (18)$$

which is plotted in Fig. 7.

We should note that it is because η is a nonlinear function of ω_m that multipath causes a phasing error that results in the improper decoding of any 38 kHz DSB-SC (double side band – suppressed carrier) signals. Let's take a specific example:

Let $|\Gamma| = 0.8$,

$$(D_2 - D_1) = 1 \text{ km},$$

$$\omega_{m19} \text{ corresponds to } 19 \text{ kHz pilot} = 2\pi \times 19 \times 10^3 \text{ rad/sec},$$

$$\text{and } \omega_{m38} \text{ corresponds to } 38 \text{ kHz} = 2\pi \times 38 \times 10^3 \text{ rad/sec}.$$

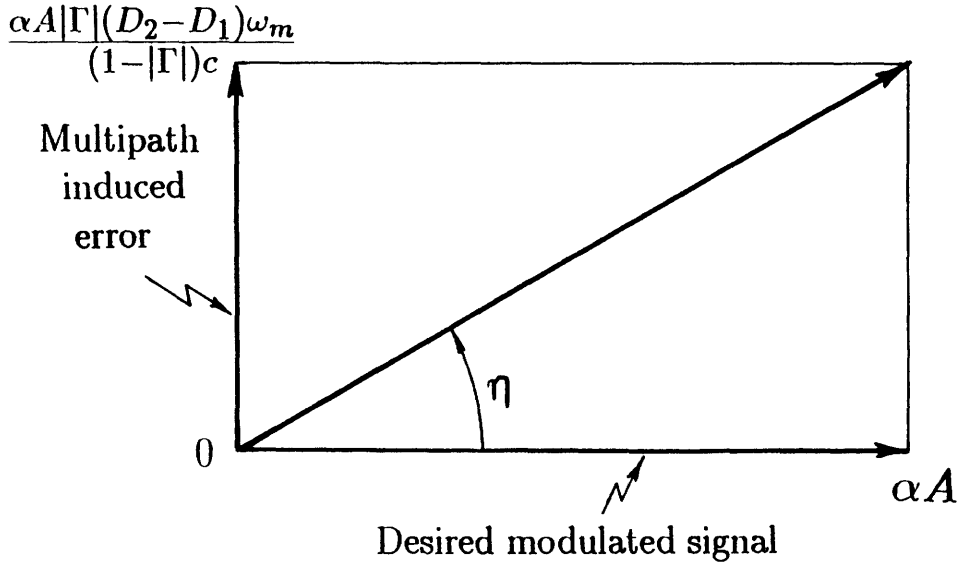
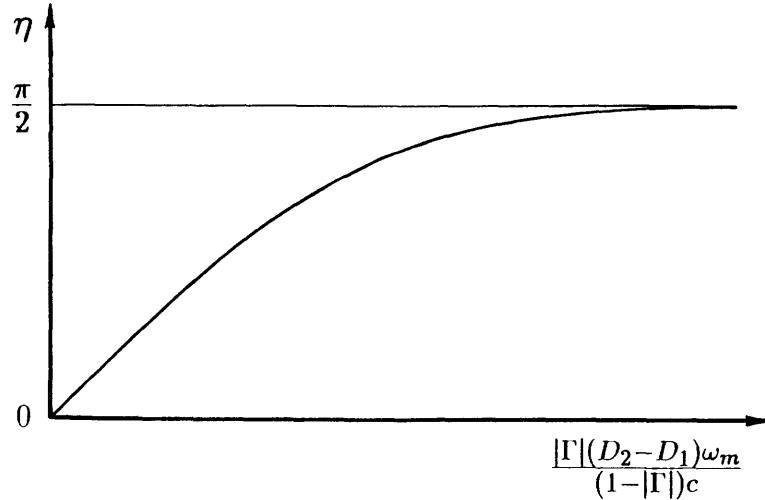


Figure 6: Phase error introduced by multipath.

Figure 7: Asymptotic limit to phase error η introduced by multipath.

(With these values and the fact that the normalized 19 kHz pilot amplitude is 0.1, the linear model is appropriate for this analysis.) For the 19 kHz pilot, from equation (18), $\eta_{19} = \tan^{-1} 1.587 = 57.8^\circ$. For the 38 kHz DSB-SC (L-R) signal, $\eta_{38} = \tan^{-1} 3.176 = 72.5^\circ$.

The phase error between the 38 kHz signal generated from the 19 kHz pilot and the 38 kHz DSB-SC signal is then $2\eta_{19} - \eta_{38} = 43.1^\circ$, which is a large error. The maximum error is 90° as $|\Gamma| \rightarrow 1$.

In a normal FM stereo broadcast, the effect of the relative phase error is to alter the level of the L-R signal as a function of the phase error. With an FMX broadcast and an FM receiver the effect is to mix varying amounts of the normal L-R and the

compressed and frequency contoured quadrature (L-R). (Note that this is in addition to the mixing discussed in the previous section.) The result can be significant volume changes and tonal changes. With an FMX broadcast and an FMX receiver the effect of the relative phase error is, as before, to mix varying amounts of the normal and compressed quadrature (L-R) signals. In addition, since the FMX receiver uses the normal FM (L-R) signal to set its expander level, the relative phase error, as well as the mixing described in the previous section, can cause the expander to operate on a mixture of the normal and compressed signals, introducing additional artifact.

4.0 Quantitative Examination of Multipath-generated Errors in the Time and Frequency Domains

Having developed insight via the vector diagram of Fig. 4 and equation (12), we are now ready to quantitatively examine multipath-generated errors. We shall compare the existing FM stereo system to the proposed FMX system. The starting point for this analysis is the following expression for $\omega_E(t)$, derived from the geometry of the vector diagram of Fig. 4.

$$\omega_E(t) = \frac{d\theta_E(t)}{dt} = \frac{d}{dt} \left\{ \frac{\theta_D(t)}{2} - \tan^{-1} \left[\left(\tan \frac{\theta_D(t)}{2} \right) \left(\frac{1 - |\Gamma|}{1 + |\Gamma|} \right) \right] \right\} \quad (19)$$

in which $\theta_D(t)$ is given by equation (9). It should be noted there are no assumptions of small signals in the derivation of equation (19). Thus, this expression is valid for all modulations of an FM carrier.

Equation (19) along with equation (9) allows us to predict the effect of multipath for any general FM signal. Next, we will apply this formula to typical FM broadcast signals, including a newly proposed FM broadcast format, FMX (refs. 1-5), developed by Broadcast Technology Partners (BTP). First, it is worthwhile to review conventional FM stereo broadcasting and the FMX system.

4.1 Review of FM Stereo and FMX

Conventional FM stereo as broadcast consists of three signals. The left and right audio channels are summed to create a compatible monophonic signal, M. In addition, the left and right channels are subtracted to create a difference channel. The difference channel is multiplied by a 38 kHz carrier, resulting in a double sideband suppressed carrier subcarrier signal, S. A pilot signal, P, at 19 kHz is also provided to allow the receiver to recreate the 38 kHz carrier needed to demodulate the S signal. These three signals are summed together to create the total composite signal that is fed to the transmitter. Fig. 8 shows a sketch of a typical spectrum.

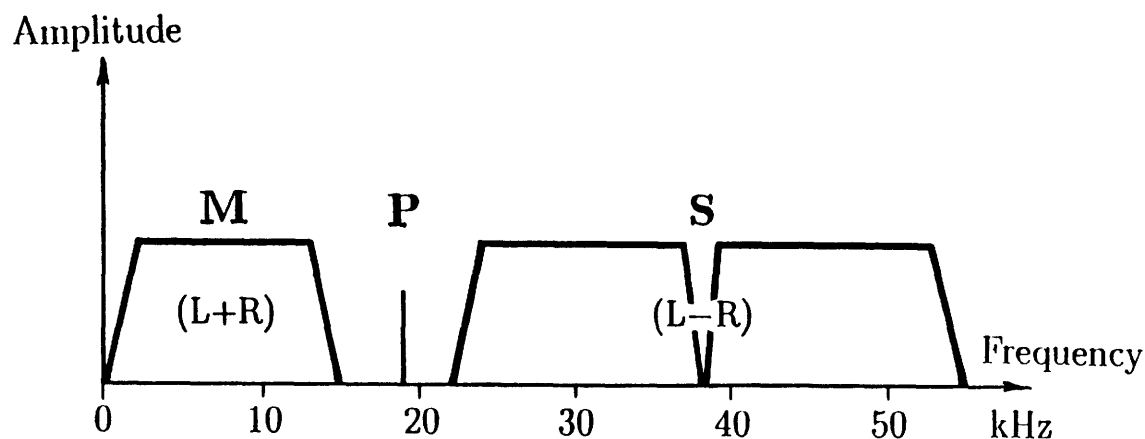


Figure 8: Spectrum of FM stereo composite audio signal.

Low level white noise added to the RF signal in the channel and in the receiver is converted at the detector output to noise that has a spectrum that is proportional to frequency, as depicted in Fig. 9. As a result, the S signal has an inherently poorer SNR than the M signal. The difference in SNR is slightly over 20 dB, when the U.S. standard 75 microsecond de-emphasis is used, and it explains the increase in background noise that is heard when switching from mono reception to stereo reception.

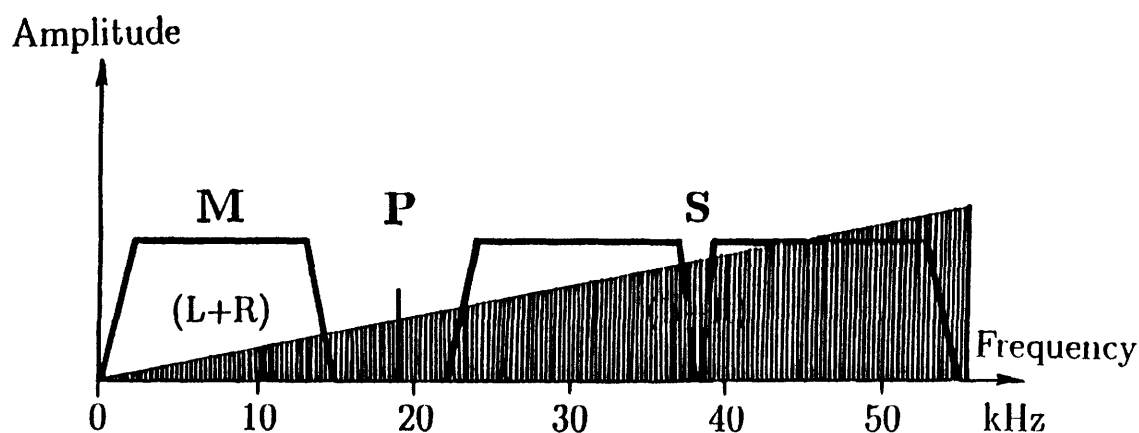


Figure 9: Spectrum of FM stereo composite audio signal showing added noise due to channel and receiver.

The FMX system attempts to improve the SNR through the use of a fourth signal added to the composite audio. The additional signal is a compressed version

of the difference channel. It is created by taking the normal difference channel and raising its level at low and moderate modulation levels, and reducing its level at high modulation levels. The proposed compression curve is shown in Fig. 10. Thus, in the receiver at low modulation levels, the compressed signal is higher above the noise level than the normal difference signal, and thus has a better SNR. At high modulation levels, where even the normal difference signal is above the noise, the compressed signal nearly vanishes, which would allow modulation levels as high in FMX as with a conventional stereo broadcast if the FMX compressor worked instantaneously.

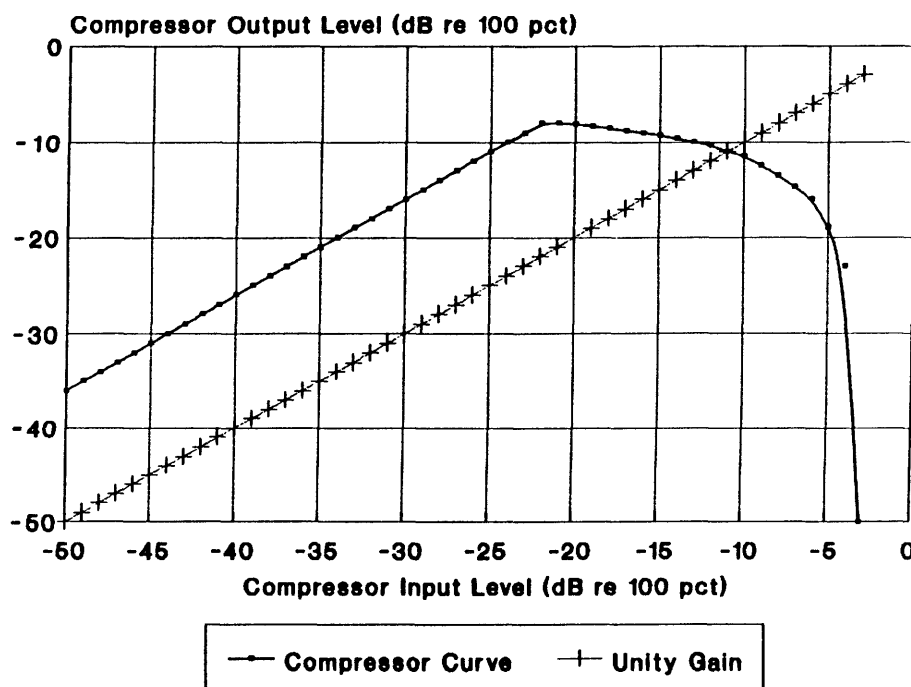


Figure 10: FMX difference channel compressor curve.

The compressed difference channel audio modulates an additional 38 kHz subcarrier in quadrature to the S signal, again using double sideband suppressed carrier modulation. This additional signal is the S' signal and is added to the conventional M, P, and S signals to create the FMX composite signal. The FMX spectrum is shown schematically in Fig. 11.

Under ideal conditions, a conventional stereo receiver would be insensitive to the S' signal, and would therefore use the M, P, and S signals to receive a normal stereo broadcast. However, an FMX receiver ideally recovers all four signals. In order to take advantage of the compressed S' signal, its level must be returned to the correct value. An expander in the receiver provides this function. The S signal, which is

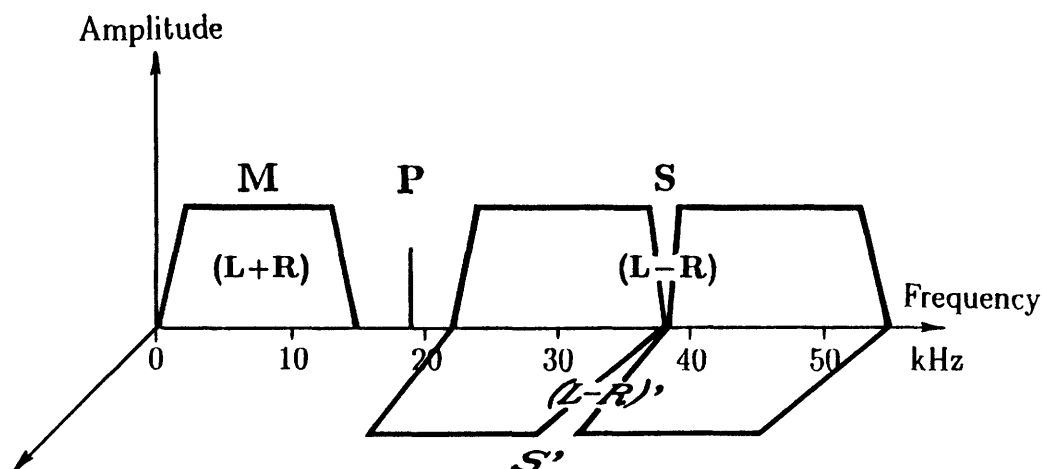


Figure 11: Spectrum of FMX composite audio signal.

at the correct level, but which is noisy, is used as a template for the compressed difference signal. The compressed difference signal, which is formed from the sum of the S and the S' signals for SNR reasons, is forced by the expander to have the same level as the S signal. The expanded difference signal is then used with the M signal to recreate the original left and right audio signals. Since the combination of the FMX compressor at the transmitter and the expander in the FMX receiver is complementary, the received audio should be identical to the transmitted audio, but with greatly improved SNR compared to conventional stereo.

To show the SNR improvement that FMX can offer, we measured the noise level with zero modulation as a function of RF signal level for mono, stereo, and FMX signals, using a prototype FMX receiver set to the appropriate receiving mode in each case. The curves are shown in Fig. 12. FMX clearly offers a SNR improvement over stereo under ideal laboratory conditions with no modulation and no multipath. As expected, however, the noise level was not as low as that of mono reception.

4.2 Multipath

The error voltage that results from demodulating the multipath signal can be calculated using equation (19). This equation was used to create a computer model which allowed us to get a quantitative feel for how multipath affects different types of transmitted signals. The graphs that follow all use a multipath model in which a single reflected path is 1000 m longer than the direct, and has a magnitude of 0.9 that of the direct, and in which the direct and reflected vectors form an angle of 170 degrees in the absence of modulation. We used the same multipath conditions for all

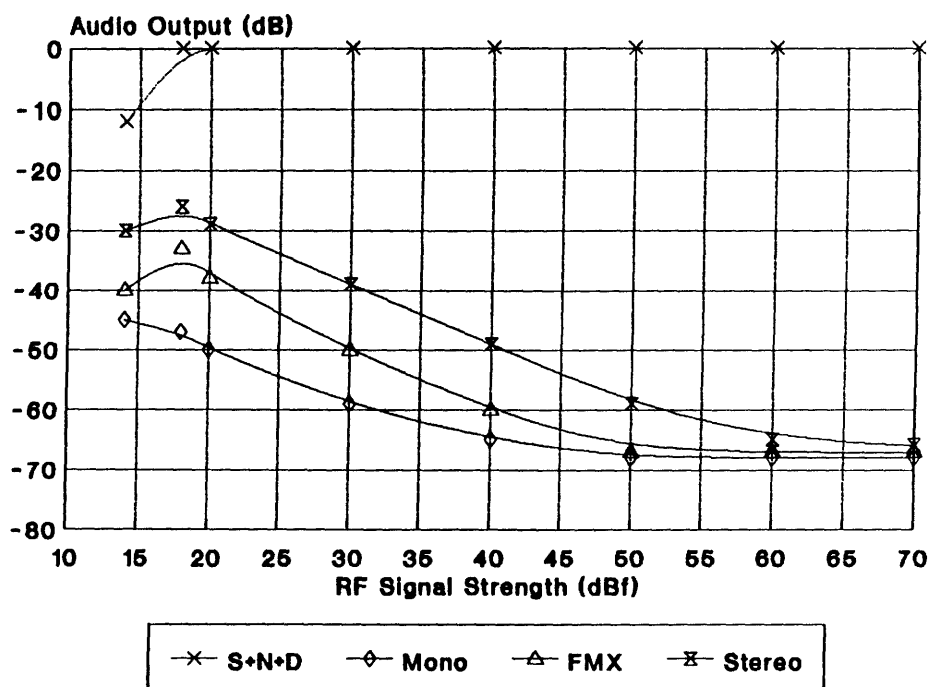


Figure 12: Measured noise as a function of RF signal level for three types of FM broadcasts.

the graphs so that they could be directly compared.

Figure 13 shows the computer simulation of a 3 kHz mono signal as transmitted and as received through this multipath environment. Figure 14 shows the simulation of a 3 kHz left channel signal in a stereo broadcast as transmitted and as received through the same multipath environment. In both, the most prominent feature of the multipath distorted waveform is the spikes that appear. Note that as predicted earlier using equation (12), the amplitude of the spikes is substantially larger in stereo than in mono, due to the presence of the high frequency subcarrier. This distortion is added at the instant that the reflected vector passes through a 180 degree angle to the direct vector. The resultant angle at this instant is changing very rapidly, and so its derivative has a very large value. Thus, the audio error voltage, which is proportional to the derivative of the angle, is very large at these instants, resulting in the spikes.

Figure 15 shows oscilloscope photographs of the detector output for a receiver in a multipath environment. The top photo used the multipath simulator built in the laboratory, consisting of RF signal splitters, attenuators, and 2000 feet of coaxial cable connected so as to simulate a one reflection multipath environment. The bottom photo was taken in the field while tuned to a musical broadcast from a regular

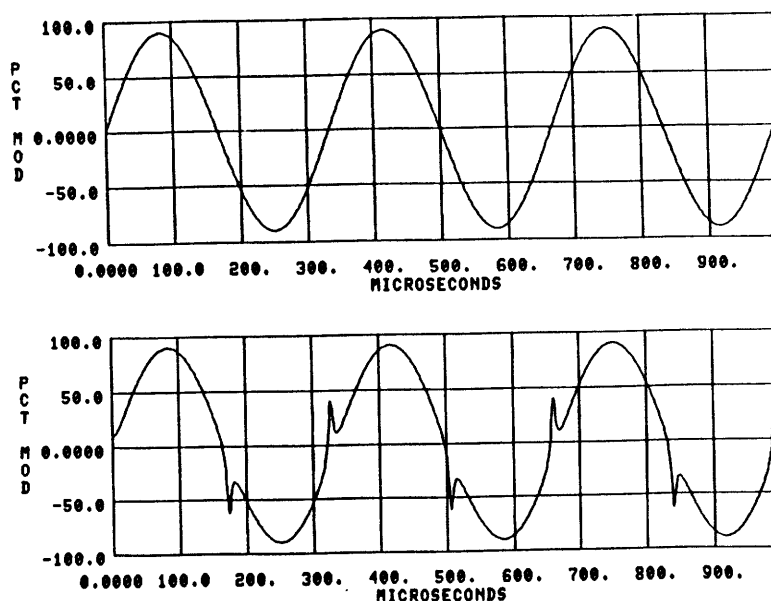


Figure 13: Time waveform of 3 kHz 90 percent mono modulation signal as transmitted (above) and as received with multipath (below).

commercial FM broadcast station. The presence of the same large spikes seen in the computer model, the laboratory simulator, and in the field helps to confirm the applicability of our model to both laboratory and field conditions.

4.3 Review of Effects Due to Multipath

With field observations that confirm our model, we felt comfortable that the model provided us with a useful tool for predicting the effects of multipath and for predicting what types of signals give the most problems in multipath.

The most obvious effect is distortion. Distortion components from the M channel appear in the S channel, and distortion from the S channel drops down into the M channel. Further, distortion from the pilot shows up as beat notes in both M and S signals. Figure 16 shows the spectrum of the composite audio signal from Fig. 14 as transmitted and received through multipath. Notice that even when the receiver reverts to mono, such that only the M signal is used, the distortion caused by multipath is still significant.

A more subtle effect is that multipath causes phase shifts between various parts of the audio spectrum, as calculated earlier. This effect can result in significant error in the demodulation of the 38 kHz subcarrier. Since the pilot is used in the receiver to regenerate the carrier needed to demodulate the S signal, multipath causes the regenerated carrier to be created with the incorrect phase. This shift causes the S

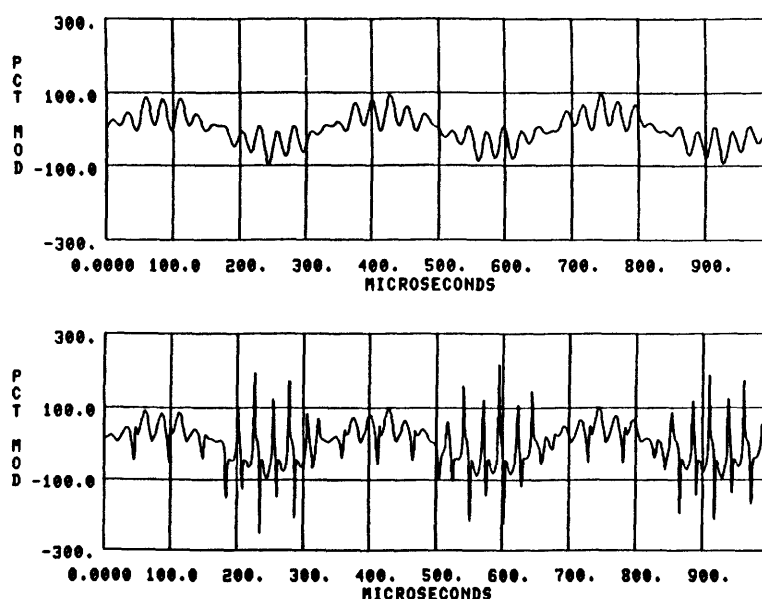


Figure 14: Time waveform of 3 kHz 90 percent left modulation composite signal as transmitted (above) and as received with multipath (below).

signal to be demodulated with the wrong amplitude. As a result, the reproduced level can vary in amplitude and the stereo sound stage can vary in width when listening to the demodulated stereo signal. Figure 17 shows the pilot phase shift using the computer simulation. The time waveform of the pilot as transmitted and as received in multipath are shown superimposed.

In order to verify qualitatively the prediction of the model, we measured the phase shift between the pilot and subcarrier in the field. Phase synchronous 19 kHz and 38 kHz sine waves were transmitted using a low power transmitter in the FM broadcast band. In a mobile receiver, the received 38 kHz was frequency divided down to 19 kHz and its phase compared to that of the received 19 kHz signal. Figure 18 shows a plot of the measured phase shift when the receiver was in a car travelling at 25 mph through a region of multipath.

Finally, another effect of multipath is that it can cause the instantaneous carrier level at the antenna to shift in level. If the level drops below limiting for the receiver, then instantaneous bursts of noise can be injected into the audio, as predicted from Fig. 4 when the two circles intersect.

4.4 Review of Factors Affecting Multipath

Equation (19) shows us directly which factors are most significant for determining the amount of error voltage created by the multipath. All other things being equal,

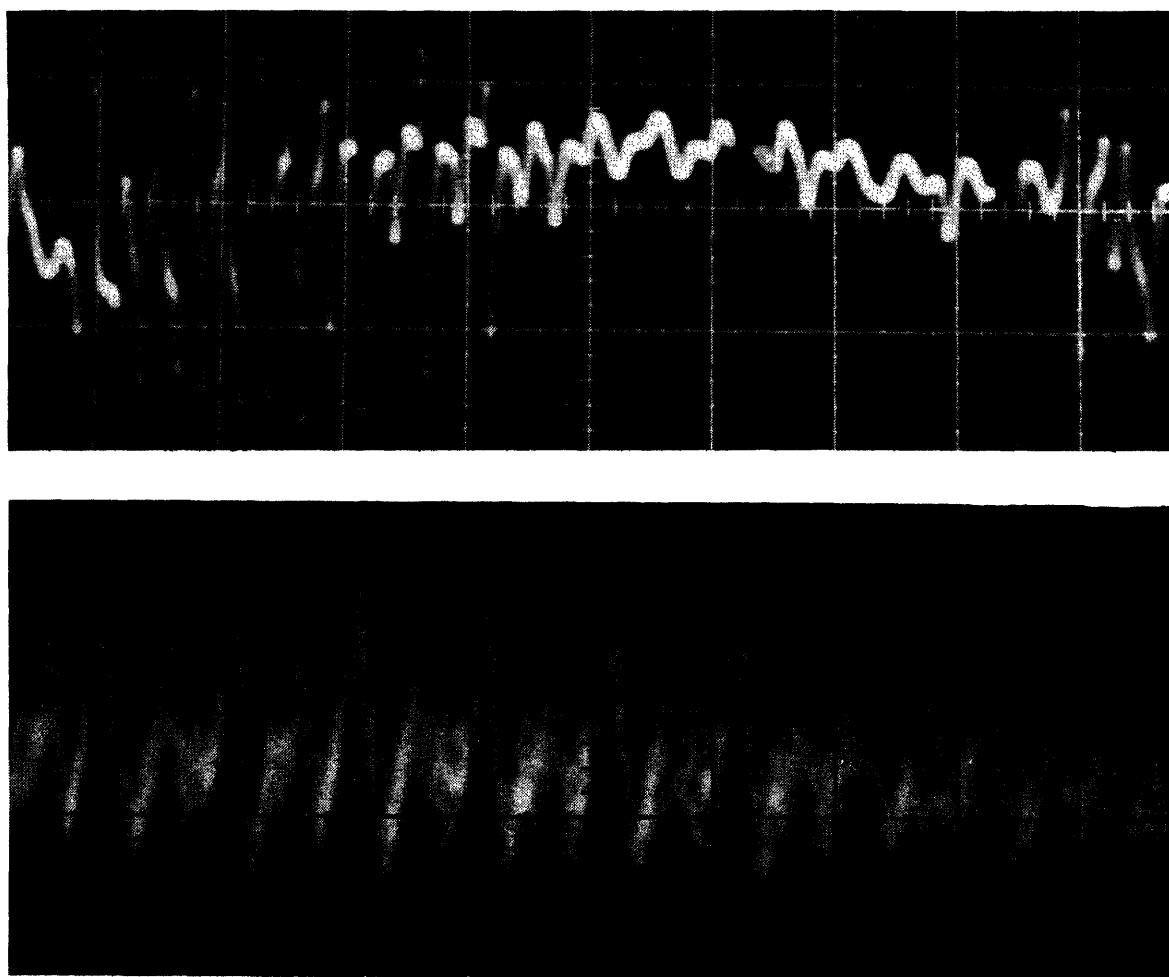


Figure 15: Laboratory (top) and field (bottom) oscilloscope photos of FM detector output showing distortion on composite signal due to multipath.

higher levels of modulation create higher levels of multipath signal distortion and noise. And, because of the time derivative in equation (19), higher frequency modulation creates more multipath distortion and noise. Therefore, the 38 kHz S signal contributes considerably more to the multipath problem than does the M signal. This is why mono broadcasts have very much reduced multipath problems compared to stereo. Additionally, SCA and other services with their high frequency subcarriers make the effects of multipath worse. Finally, longer path length differences between direct and reflected paths, with all other conditions held constant, make multipath effects worse.

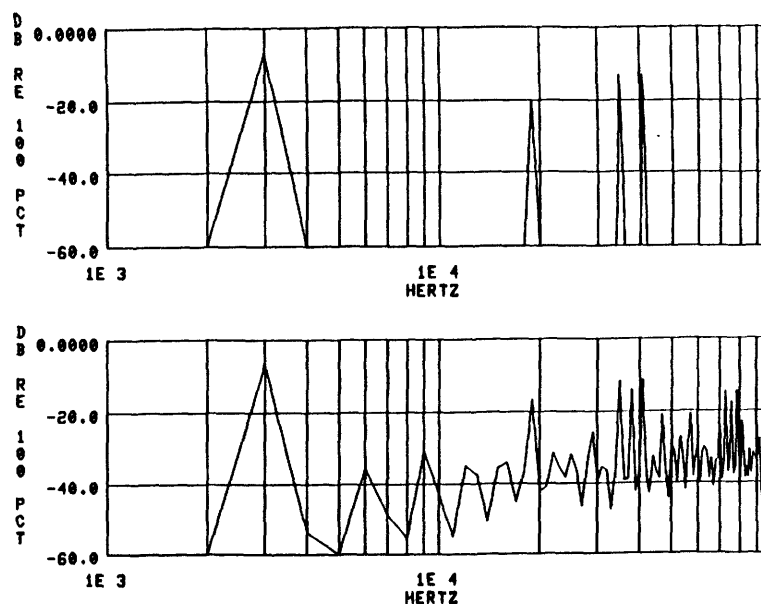


Figure 16: Spectrum of 3 kHz 90 percent left modulation composite signal as transmitted (above) and as received with multipath (below).

4.5 Multipath and FMX

From the analysis presented earlier, it follows that an FMX broadcast suffers from multipath more than conventional stereo for three reasons:

1. more high frequency energy
2. pilot phase errors causing crosstalk between S and S'
3. quadrature distortion components causing crosstalk between S and S'

As we will show below, an FMX broadcast as received on a conventional receiver has

1. increased distortion
2. increased noise
3. increased stereo soundstage motion
4. increased volume level changes
5. timbre changes

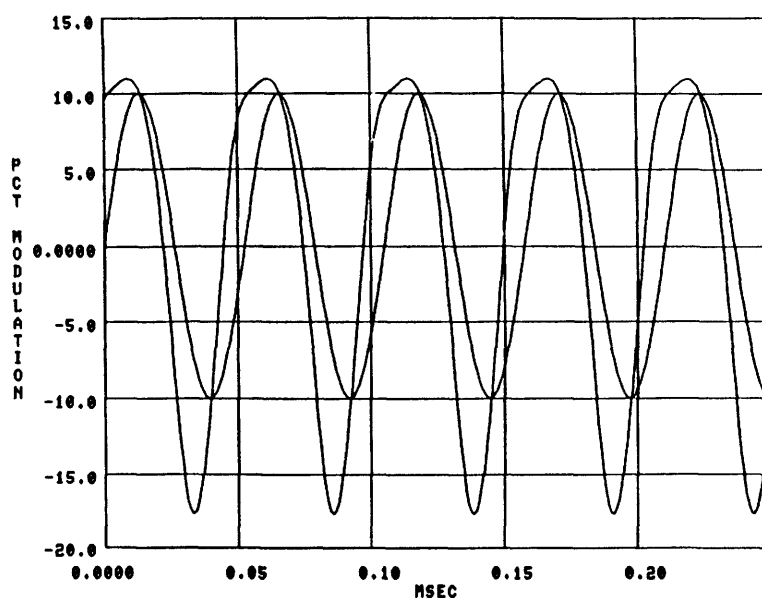


Figure 17: Time waveform of pilot as transmitted and as received with multipath.

compared to a conventional FM stereo broadcast.

The compressed S' signal results in considerably more high frequency energy than a conventional stereo signal in all cases except high modulation levels as we have shown. The additional high frequencies cause multipath effects to be more severe for an FMX broadcast than for a conventional stereo broadcast, regardless of reception mode. Figures 19, 20, 21 and 22 show this result using the computer simulation. The time waveforms of the transmitted composite signal for both an FMX and a conventional FM stereo broadcast are shown in Fig. 19. Figure 20 shows the time waveform of the received signals after they have passed through identical multipath environments. The spectrum of the transmitted composite signal is shown in Fig. 21. Figure 22 shows the spectrum of the received signals. The FMX signal has considerably more distortion, not only in the S signal, which a conventional stereo receiver reproduces, but even on the M signal, which a mono receiver or a blended stereo receiver reproduces. Figure 23 shows the demodulated S signal spectrum in the presence of multipath for an FMX broadcast and for a conventional FM stereo broadcast. It is this S signal that a conventional FM stereo utilizes to recreate the original left and right audio signals. The difference in distortion between the two received signals is obvious.

The second reason was discussed earlier in section 3.4. Because of the multipath generated phase shift between the pilot and the subcarriers, a conventional stereo receiver no longer decodes only the S signal, but rather some combination of the S and

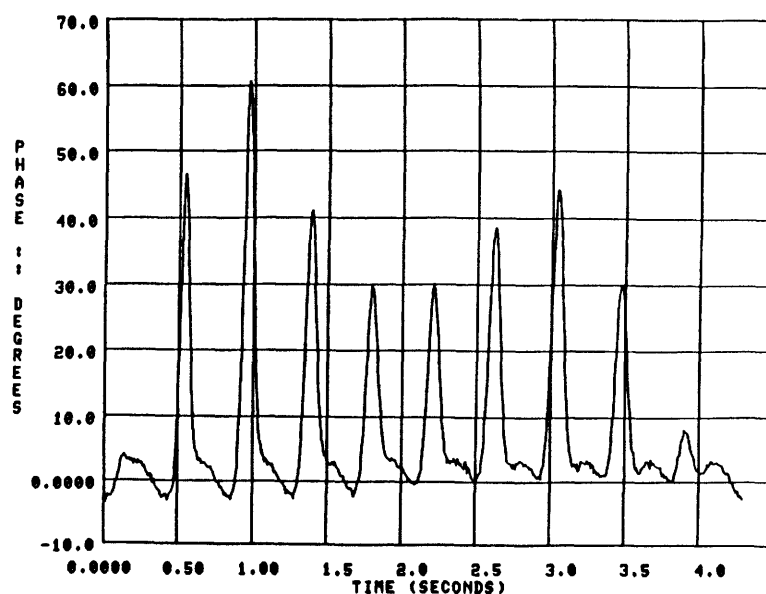


Figure 18: Measured phase shift between 19 kHz pilot and 19 kHz signal derived from 38 kHz subcarrier while travelling through a region of multipath in the field.

S' signal. As a result, the level of the received difference channel changes as the level of the music changes. This difference channel level shift varies with modulation, and causes two effects. First, the stereo sound stage expands and contracts as the music changes. And, because the S' channel has a different pre-emphasis than the S channel, the recovered difference channel, which is a combination of S and S', has a frequency balance which changes as the level of the music changes, causing a change in the timbre of instruments. The effect can range from the minor to major, depending on the music, and on the multipath conditions. With a mobile receiver, the momentary interchange of S and S' results in severe difference channel level errors, causing a "barking" effect, where the level of the reproduced music momentarily jumps up as much as 14 dB, and then returns to normal as the receiver passes out of a region of multipath. This effect, which occurs during stereo reception of an FMX broadcast, becomes even more pronounced with FMX reception. During FMX reception of an FMX broadcast, S' crosstalk into the S channel due to phase errors causes further amplitude errors, because the FMX expander operates based on the level of the S channel. Since, in regions of multipath, the S signal is corrupted by crosstalk from the S' signal, the expander operates based on faulty information, resulting in incorrect expander performance, compounding the amplitude error effect.

The crosstalk between S and S' is shown through the use of computer simulation

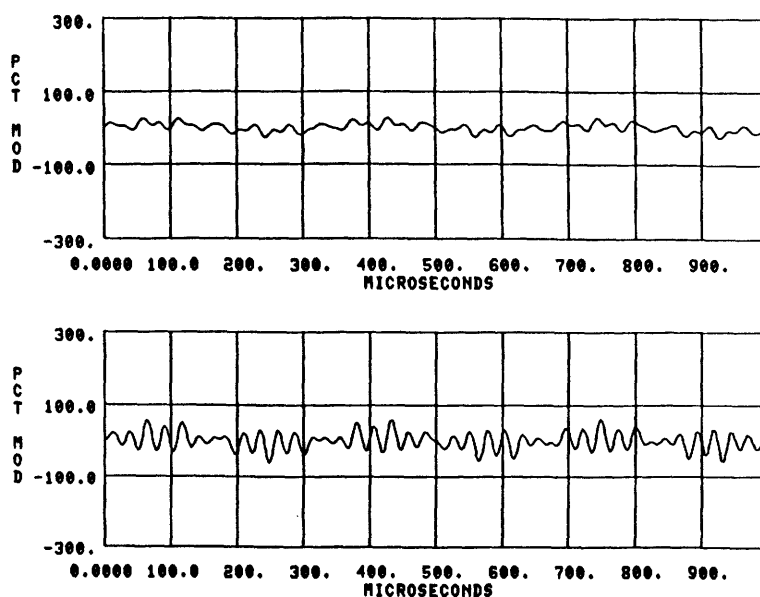


Figure 19: Time waveform of 3 kHz 20 percent left modulation composite signal as transmitted for conventional FM stereo broadcast (above) and for FMX broadcast (below).

in Figures 24 and 25. The figures show demodulated S and S' signals for an FMX broadcast. The top graph of Fig. 24 shows the S signal as transmitted, while the bottom graph shows the S signal as received in the presence of multipath. Similarly, Fig. 25 shows the S' waveform as transmitted and as received with multipath. The S signal with multipath shows a substantial increase in level, due to the crosstalk between S and S' . The crosstalk causes the effects described in the previous paragraph.

The third reason also has its origin in the discussion in section 3.3. However, it has nothing to do with the phase shift of the pilot. As we have seen, multipath generates a quadrature component to any signal. Thus, multipath causes an S' signal to create quadrature distortion components, which add to the S signal and vice versa. These distortion components contribute to the crosstalk between the S and S' signals. The effects are similar to those described in the previous paragraph.

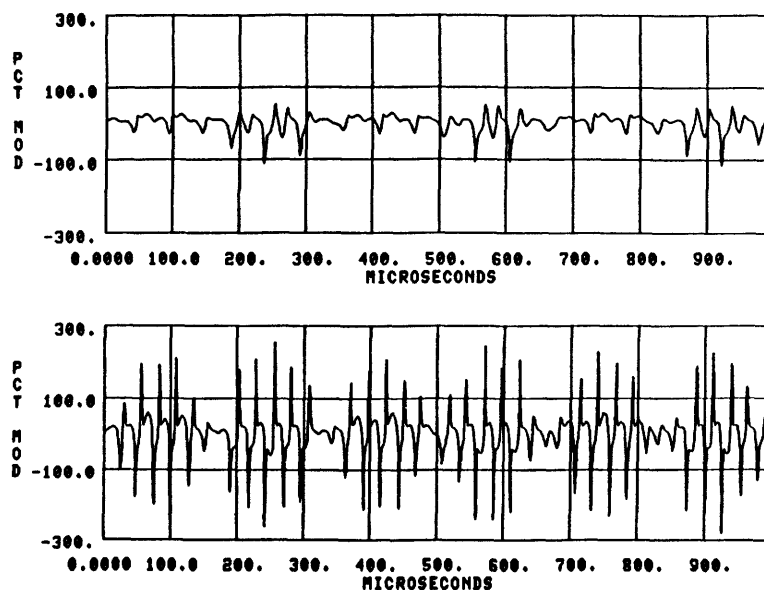


Figure 20: Time waveform of 3 kHz 20 percent left modulation composite signal as received with multipath for conventional FM stereo broadcast (above) and for FMX broadcast (below).

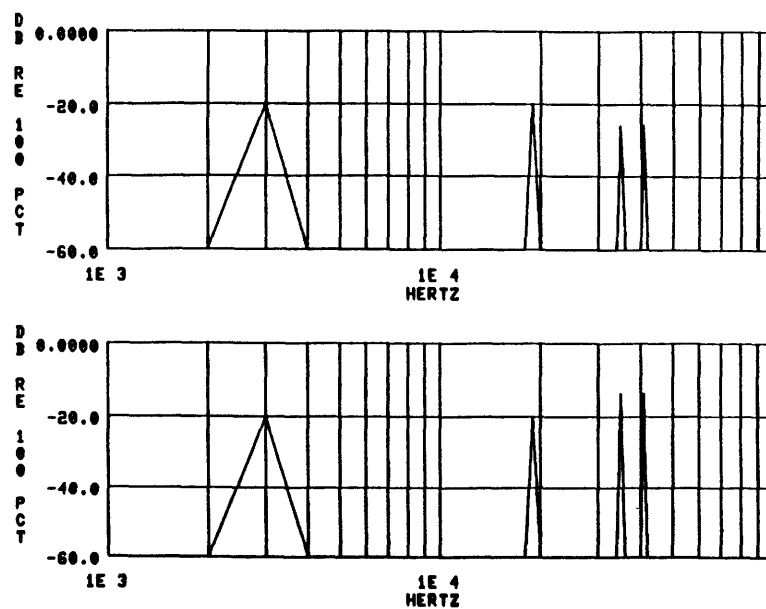


Figure 21: Spectrum of 3 kHz 20 percent left modulation composite signal as transmitted for conventional FM stereo broadcast (above) and for FMX broadcast (below).

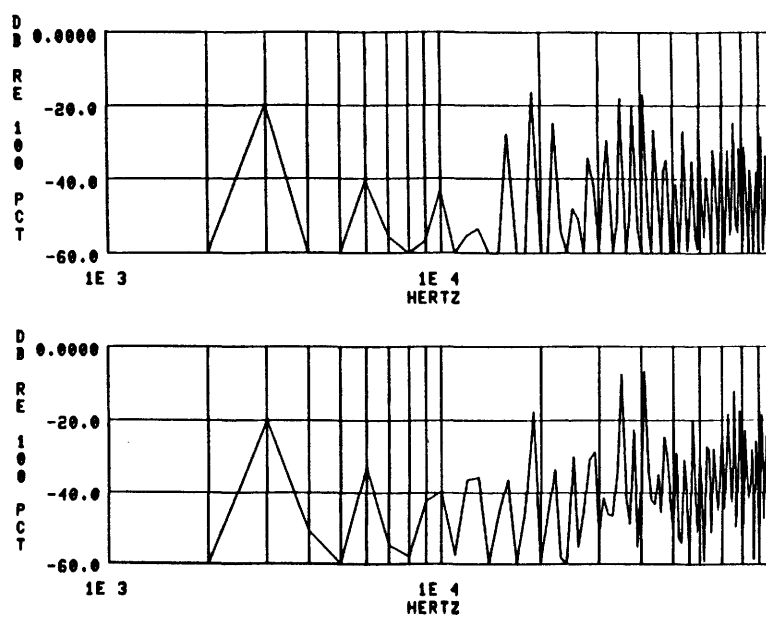


Figure 22: Spectrum of 3 kHz 20 percent left modulation composite signal as received with multipath for conventional FM stereo broadcast (above) and for FMX broadcast (below).

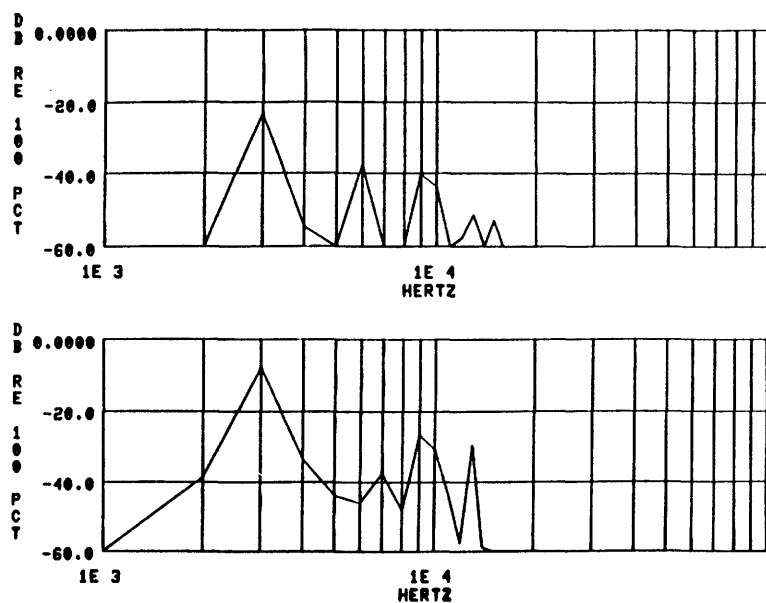


Figure 23: Spectrum of decoded S channel audio for 3 kHz 20 percent left modulation as received with multipath for conventional FM stereo broadcast (above) and for FMX broadcast (below).

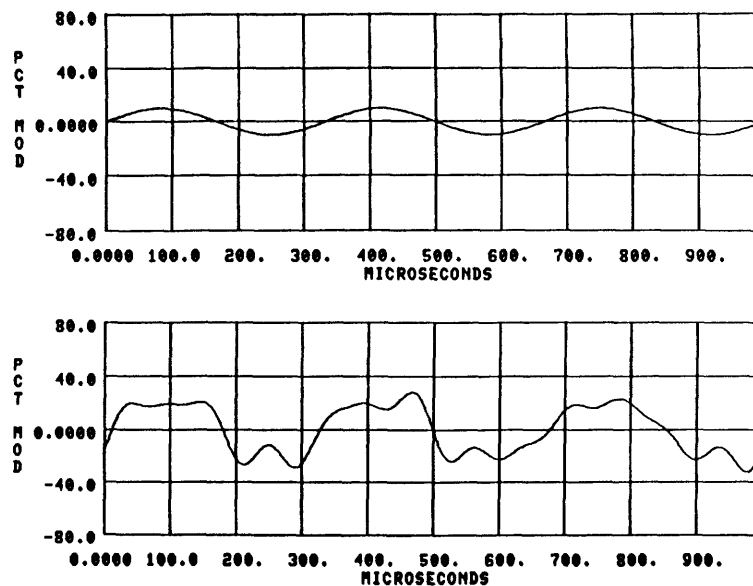


Figure 24: Time waveform of decoded S channel audio for 3 kHz 20 percent left modulation FMX broadcast as transmitted (above) and as received with multipath (below).

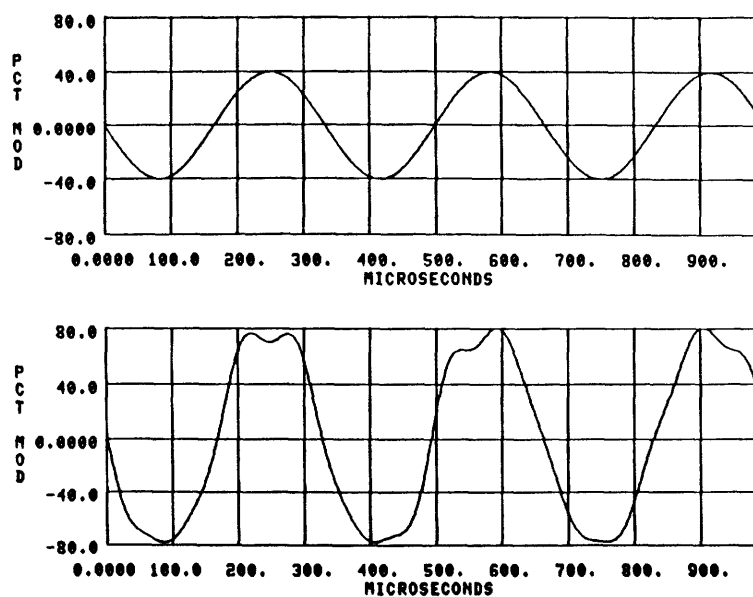


Figure 25: Time waveform of decoded S' channel audio for 3 kHz 20 percent left modulation FMX broadcast as transmitted (above) and as received with multipath (below).

4.6 Over the Air Experiments

In order to quantify the effects of FMX we heard with music, we performed an experiment using the facilities of WMBR, the radio station of the Massachusetts Institute of Technology. WMBR broadcasts on a frequency of 88.1 MHz, serving the MIT and Cambridge communities. At the time of the experiments, its effective radiated power (ERP) was 200 watts. Its transmitter and antenna are located on top of the Eastgate building some 24 stories above Kendall Square in Cambridge. Although the ERP of the station is considerably less than typical commercial broadcast stations, the lower power does not effect any of the conditions that we measured. The only effect is that the conditions we found would occur closer to the transmitter than with a higher power station.

A commercial FMX generator (Inovonics model 705) was installed at the WMBR transmitter in accordance with manufacturer's recommendations. BTP believes that synchronous AM of the RF signal is an important parameter for FMX. Our measurement of AM on the WMBR carrier due to all causes was lower than BTP's recommendation for synchronous AM alone. Additionally, audio distortion measurements through the entire WMBR signal path in the FMX mode while receiving in the FM stereo mode using the WMBR off air monitor (which receives a multipath-free signal) at the studio indicated substantially less than one percent distortion over a variety of test signals. All these measurements gave us confidence in the quality of the WMBR broadcast signal.

Our goal was to determine over what percentage of the coverage area of the station the broadcast signal was degraded by multipath and other field conditions when using FMX compared to conventional FM stereo. To achieve this goal, we needed to make audio measurements on the received WMBR signal at many locations throughout the coverage area of the station. We could do this by sending someone to many fixed locations to make the measurements. Alternatively, we chose to design an experiment using a moving receiver, sampling the data at many locations as the vehicle drove through the coverage area. Then, in the laboratory, these samples were processed by computer to give the same results as if we had made measurements at many fixed locations, each of which represented the average over a one-meter distance.

We broadcast a 1 kHz sine wave at 20 percent modulation level on the left channel only, using both conventional FM stereo modulation, and using the FMX system. This level is the highest that allows maximum compression in FMX. A mobile receiver was driven along a fixed path, covering both the primary coverage area of the station, as

well as secondary and fringe areas. The route included: Memorial Drive in Cambridge, which we refer to as urban; the Massachusetts Turnpike from Allston to Newton, which we refer to as suburban; and Route 128 from Newton to Waltham, which we refer to as fringe. The path covered, as well as the measured RF signal levels for the station are shown in Fig. 26. Two way radio communication between the car and the WMBR transmitter permitted instantaneous switching of transmitter mode from the vehicle.

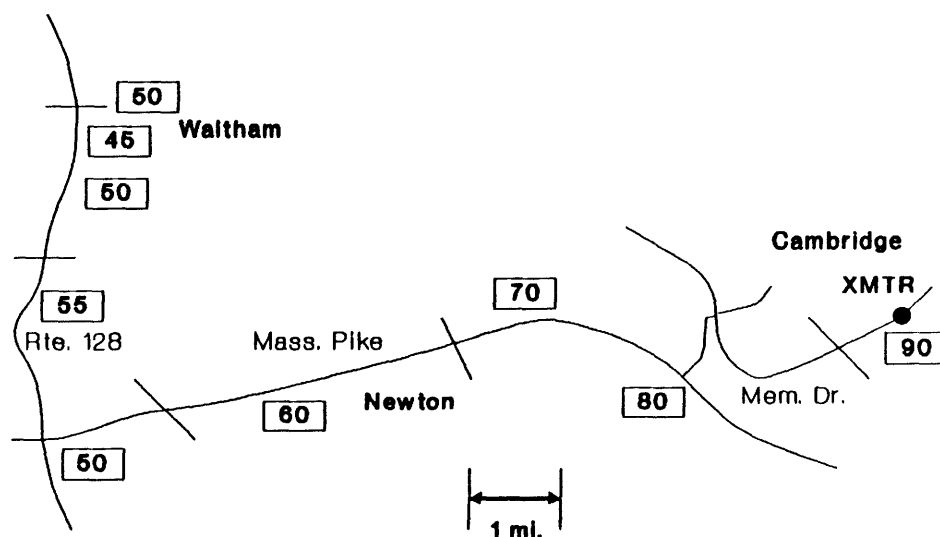


Figure 26: Map of experimental route showing received WMBR RF signal strength in dBm from 1 meter whip antenna on car roof.

The receiver stereo audio outputs were recorded digitally on tape for later analysis in the laboratory, for a variety of receiver conditions. In the laboratory, the tape was played back, first through a narrow band ($Q=50$), band pass filter centered at 1 kHz, and then through a narrow band, band reject filter (with more than 60 dB rejection of the 1 kHz signal). The filter outputs fed average level detectors, whose outputs were low pass filtered at 10 Hz, sampled, and stored. With this apparatus, we were able to acquire and store the signal levels of the left and right channels, and the distortion and noise levels of the left and right channels for long periods of time at a series of locations separated about every one meter in each of the urban, suburban, and fringe regions. This process allowed us to acquire data for approximately 15,000 locations throughout the coverage area of WMBR. The data include all conditions as they exist in the Boston area, including regions with multipath and regions without multipath.

Three different broad classes of receiver and transmitter conditions were consid-

ered: conventional FM stereo transmission with conventional FM stereo reception; FMX transmission with conventional FM stereo reception; and FMX transmission with FMX reception. When using conventional FM stereo reception, we made recordings both with and without a conventional blend circuit. A blend circuit reduces perceived noise by gradually, or in some cases, abruptly, reducing the gain of the S signal applied to the stereo matrix. Most mobile receivers use blend circuits. We chose to make measurements both with and without blend so that the blend would not mask the effects of multipath. Recall that we were not trying to assess the problems of mobile reception as much as we were trying to sample a large number of receiving sites in an efficient manner. Any one of these receiving sites might be the location of a home receiver, where blend may or may not be in use.

In the case of FMX reception, we also made tapes both with and without the expander hold circuit suggested by BTP (ref. 5). In the presence of multipath, noise in the S and S' channel can cause incorrect expansion of the S' channel. If this noise burst is brief, as can be the case with mobile reception, the audible effects of the noise burst can be reduced by holding the amount of expansion until the noise burst has passed. In the case of home reception, such a circuit will be of limited use. In this situation, a multipath problem is likely to persist for an extended period of time or even permanently, and holding the amount of expansion for such a length of time is likely to cause extremely large errors in expansion. Since we were trying to assess the effects of FMX not so much for mobile use as for a large number of fixed points, we made measurements both with and without the expander hold.

Our prototype FMX receiver incorporated blend, but listening to WODS, a high power commercial station in Boston operating with FMX, showed that the receiver never unblended except over small regions, throughout the entire portion of the suburban and urban regions of our test route. The significant benefit that BTP promotes for FMX is the preservation of stereo in marginal signal conditions.

"The commonly-employed 'blend' function reduces some of this multipath noise in conventional receivers, but at the expense of reduced stereo separation. In contrast, FMX receivers provide reduction in background noise without a loss of stereo separation." (ref. 5)

Therefore, it only makes sense to evaluate the system in stereo, not as a fully blended mono signal. As a result, we chose not to make any measurements using FMX with blend.

The antenna and receiver through to the detector output was the same in all experiments. The antenna was a 1 meter whip antenna mounted on the roof of the automobile. The receiver was an Alpine receiver used in the Acura/Bose automotive sound system. For the experiments using FM stereo reception with blend, this receiver was operated in a completely unmodified mode, and as such, represents a substantially better than normal auto radio. For the experiments using FM stereo reception without blend, or using FMX reception, the detector output of the Alpine receiver fed a Sanyo LA3440 FMX decoder chip (ref. 6), used and adjusted as per manufacturer's recommendations. While this chip is still in prototype form, BTP claimed that it was adequate for demonstrating the FMX system.

Typical raw data curves are shown below in Figs. 27 through 32. Figure 27 shows the left and right channel signal level (i.e. the output of the bandpass filter) in three different regions, the urban, suburban, and fringe regions. The broadcast is conventional FM stereo, while the receiver is conventional FM stereo without blend. The vertical axis indicates amplitude level, and the horizontal axis indicates time. Since the vehicle was moving, time translates into space, and the curves therefore indicate level at many different locations throughout the coverage region. The top curve shows the left channel signal level, which, with 20 percent modulation, should be at a level of -14 dB in the absence of multipath. The portion beginning at $t = 0$ seconds is taken from the urban region, the portion beginning at $t = 100$ seconds is taken from the suburban region, and the portion beginning at $t = 200$ seconds is taken from the fringe region. The bottom curve shows the right channel signal level, which, due to imperfect stereo separation even under ideal conditions, is not zero. As before, urban, suburban, and fringe regions are separated. Note that in many places, left channel levels decrease while right channel levels increase, which are the result of the phase shifts between P and S signals discussed earlier. Such phase shifts cause incorrect demodulation of the difference signal, reducing the level of the difference channel. In the case of left only modulation, this difference channel amplitude error causes the left channel level to decrease while the right channel level increases. Increases in the left channel level occur as a result of the generation of quadrature components caused by multipath as shown earlier.

Figure 28 shows similar curves for the case of FM stereo transmission and FM stereo reception with a blend circuit active. Here, there are many instances where left channel level increases and right channel level decreases to the point where they are the same, i.e. mono reception. This is clear evidence of the blend circuit in action.

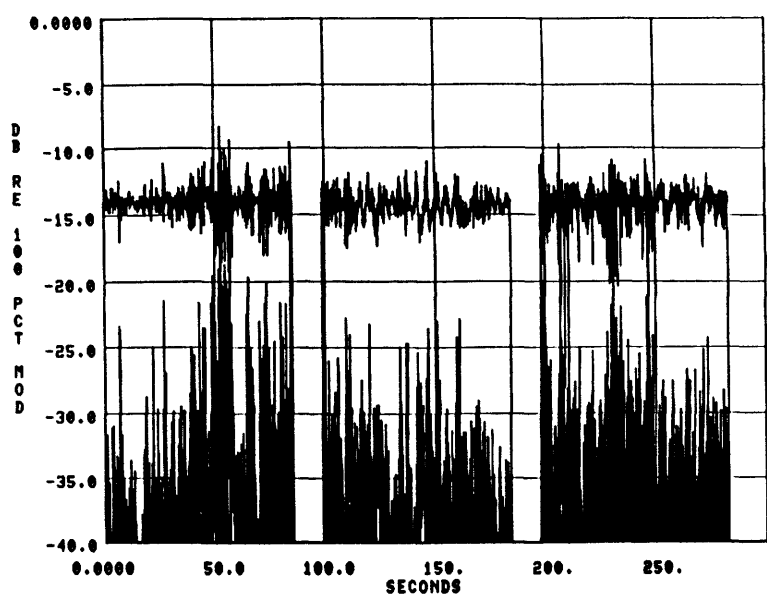


Figure 27: Left and right channel signal level with FM stereo transmission and FM stereo reception without blend.

Figure 29 shows the curves for the case of FMX transmission with FM stereo reception and no blend. These curves show many instances where left and right channel amplitudes drastically increase. This effect can be explained by the phase shift between the P and S signal due to multipath. In this case, the phase shift causes crosstalk between the S and S' signal, resulting in a demodulated S signal having a much higher level than is correct. This error causes both L and R audio levels to be too high.

Figure 30 shows the same conditions but with the blend circuit activated. The blend circuit can be seen to be effective in reducing many of the high amplitude errors. In the presence of multipath, the blend may be activated, thus eliminating the audible effects of the S and S' signal interchange. However, because the amount of multipath is increased, due to the higher level of high frequency signals present in the FMX broadcast, blending takes place much more frequently than in the case of FM stereo transmission, with the consequent loss of stereo separation. Note that in the fringe region, there are extended regions where the signal is fully blended.

Figure 31 shows the case of FMX transmission and FMX reception. Here, the problems of S and S' interchange are compounded by expander errors. Once again, very large amplitude errors are caused by phase shifts which result in S and S' interchange, which when expanded, cause even further errors.

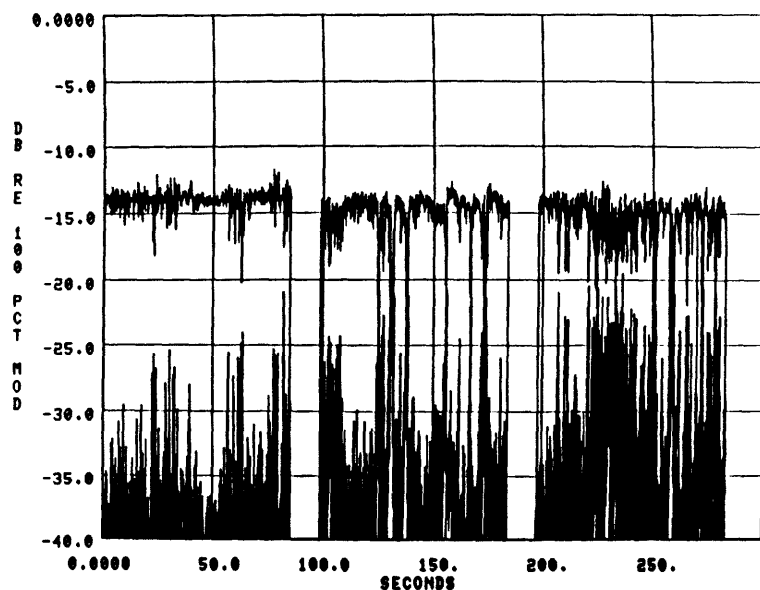


Figure 28: Left and right channel signal level with FM stereo transmission and FM stereo reception with blend.

Figure 32 shows the effect of adding the expansion hold circuit that BTP proposed (ref. 5). Interestingly, the data show that this approach does not seem to correct the amplitude errors in the high amplitude direction, but does seem to reduce those in the low amplitude direction.

Figures 33 through 38 show the distortion and noise level (i.e. the output of the band reject filter) for the left channel only under the same six conditions. The curves are self explanatory. It can be seen that the blend circuit used with FM stereo reception does much to reduce distortion and noise by reducing the level of the S signal during periods of weak signals or multipath. It can also be seen that the expander hold used with FMX reception introduces substantial additional distortion or noise.

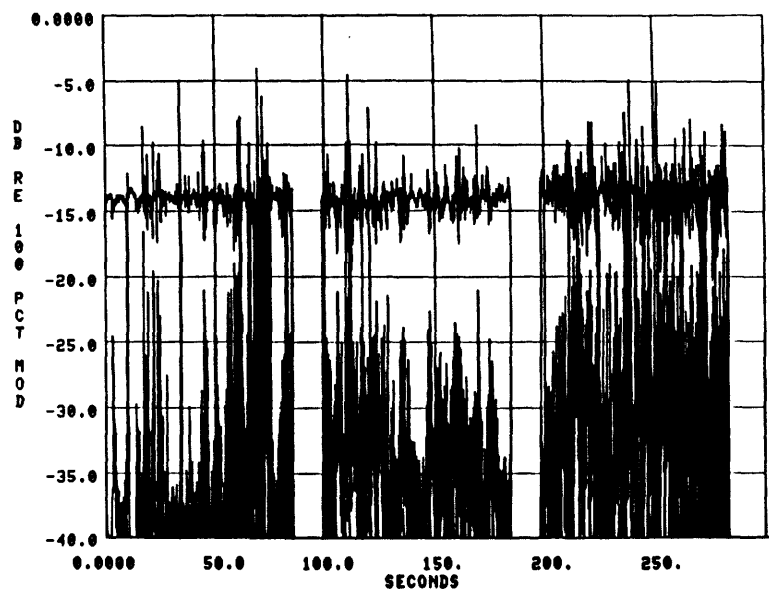


Figure 29: Left and right channel signal level with FMX transmission and FM stereo reception without blend.

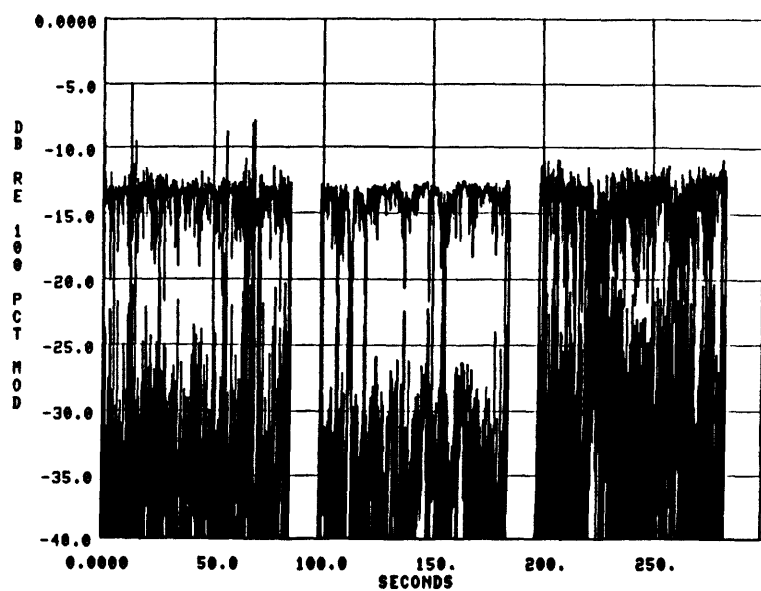


Figure 30: Left and right channel signal level with FMX transmission and FM stereo reception with blend.

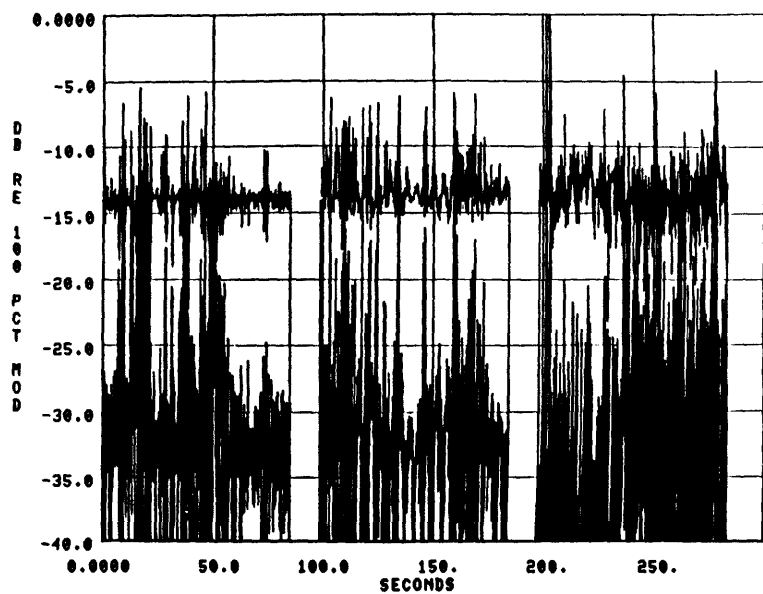


Figure 31: Left and right channel signal level with FMX transmission and FMX reception without hold.

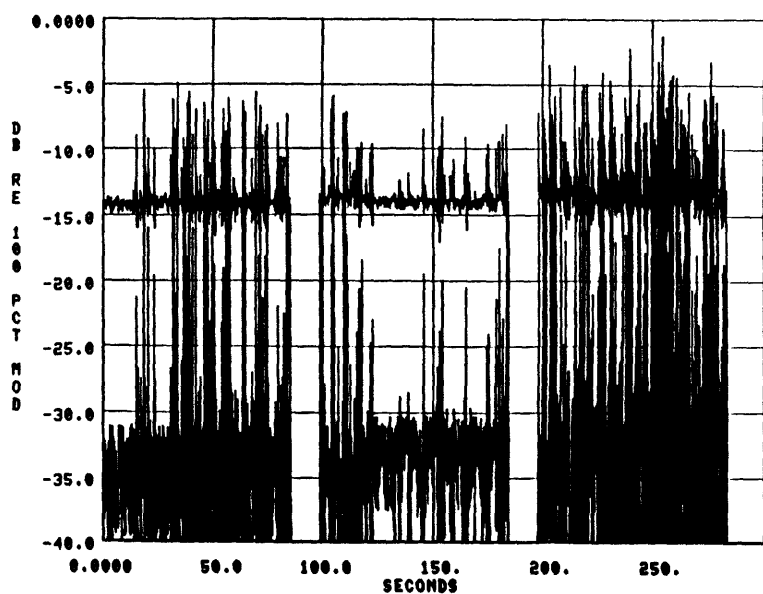


Figure 32: Left and right channel signal level with FMX transmission and FMX reception with hold.

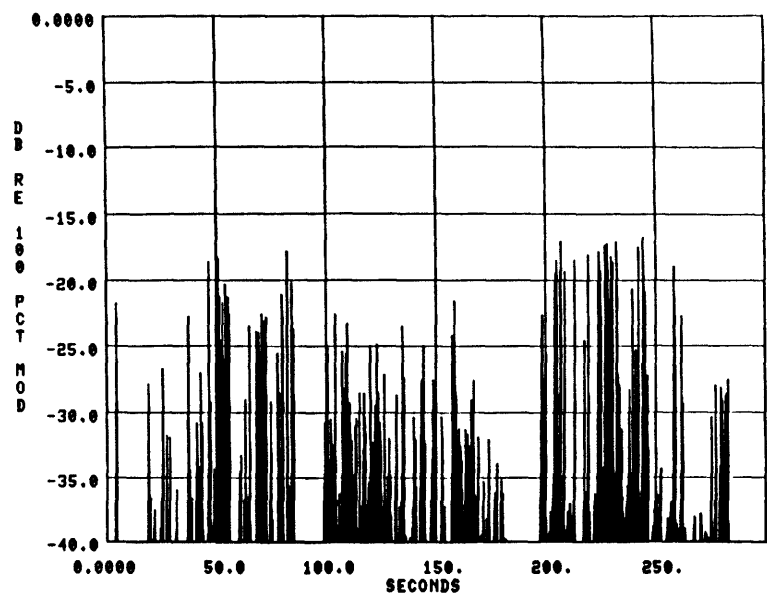


Figure 33: Left channel distortion and noise level with FM stereo transmission and FM stereo reception without blend.

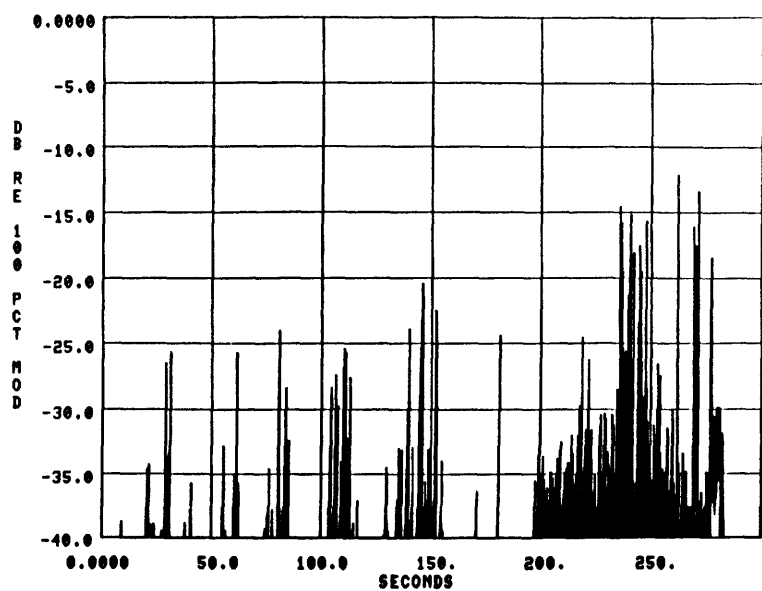


Figure 34: Left channel distortion and noise level with FM stereo transmission and FM stereo reception with blend.

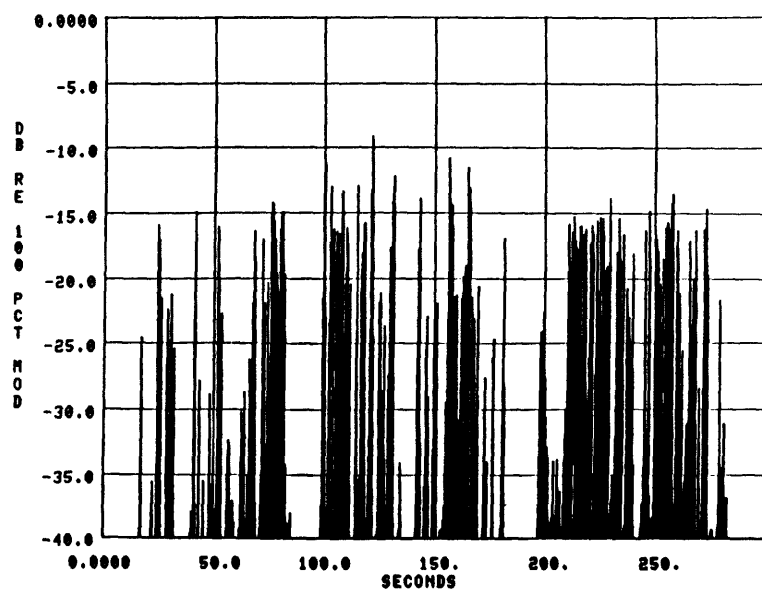


Figure 35: Left channel distortion and noise level with FMX transmission and FM stereo reception without blend.

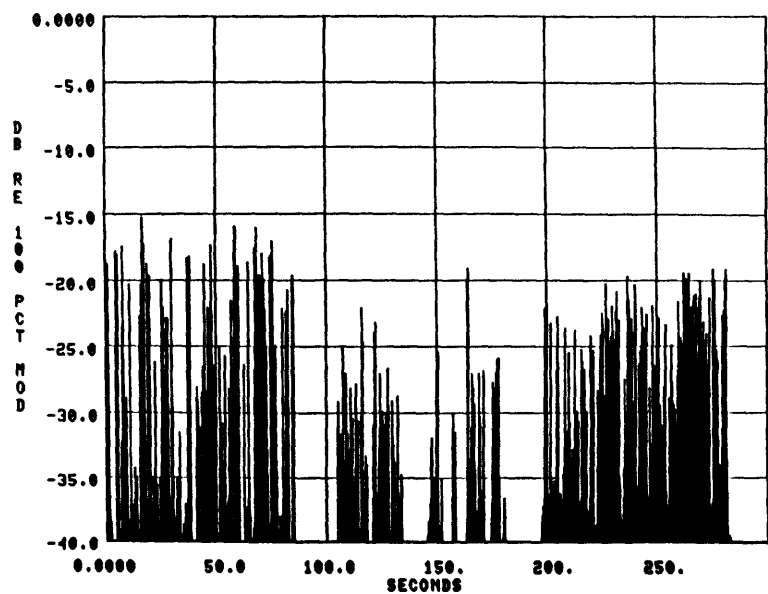


Figure 36: Left channel distortion and noise level with FMX transmission and FM stereo reception with blend.

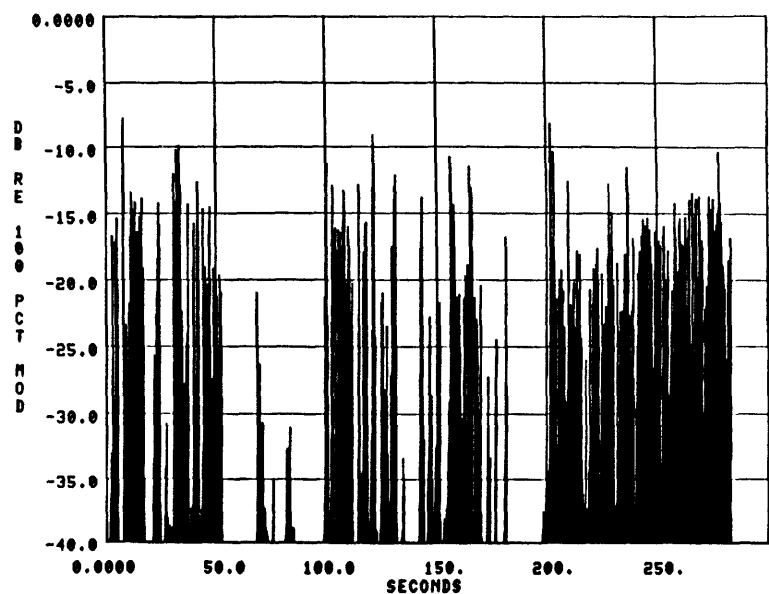


Figure 37: Left channel distortion and noise level with FMX transmission and FMX reception without hold.

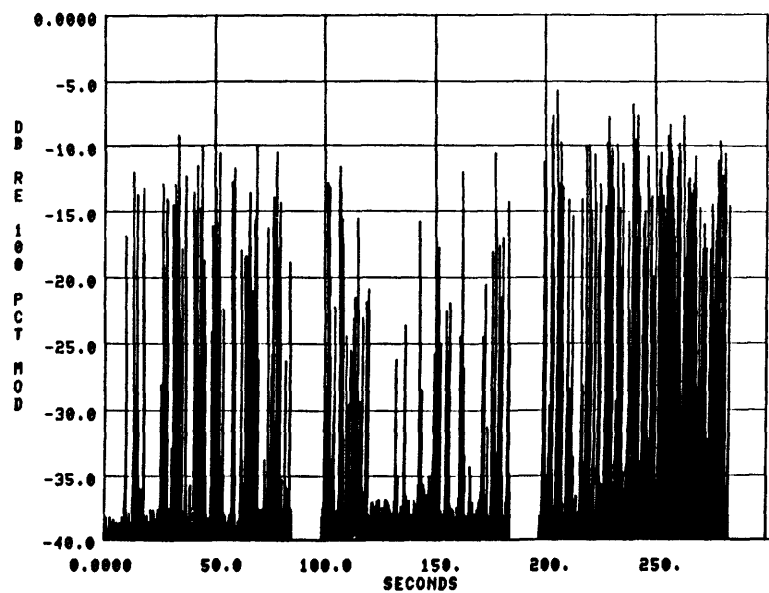


Figure 38: Left channel distortion and noise level with FMX transmission and FMX reception with hold.

4.7 Analysis of Data

All these data lead us to the conclusion that the FMX system degrades the coverage of a broadcast station. However, we further analyzed the data to quantify the amount of degradation. For each of the six conditions of receiver and transmitter, we determined for what percentage of the samples certain parameters exceeded various thresholds. For each of the six conditions considered, over 15,000 sample points were considered, corresponding to 15,000 different receiving locations throughout the coverage area of the station.

Figure 39 shows the results for the parameter of left channel amplitude errors where the received audio signal has a greater amplitude than the transmitted audio signal. The three conditions shown are: FM stereo transmission with FM stereo reception; FMX transmission with FM stereo reception; and FMX transmission with FMX reception. In each case, blend or expander hold was not used. The graph shows that in over 10 percent of the samples, the received amplitude error was greater than 2 dB with FMX transmission and reception, as compared to 1.2 percent for FM stereo transmission and reception. This means that in the case where only 1.2 percent of receiving locations had audible amplitude errors using FM stereo transmission and reception, that 10 percent, or eight times as many receiving locations, would have similar amplitude errors using an FMX broadcast and receiver. Even in the case where the broadcaster uses FMX but the listener uses FM stereo, twice as many receiving locations will have audible amplitude errors compared to when the broadcaster uses FM stereo. Further, 1 percent of the receiving locations when FMX transmission and FMX reception is used have amplitude errors exceeding 6 dB, a one hundred percent error in level, compared with nearly 0 percent using an FM stereo system. Note that in each case, more receiving locations have amplitude errors when FMX transmission and conventional FM stereo reception is used than when conventional FM stereo transmission and conventional FM stereo reception is used. Further, more receiving locations have amplitude errors when FMX transmission and FMX reception is used than when FMX transmission and conventional FM stereo reception is used.

Figure 40 shows similar data when blend or hold is used. Again, large number of receiving locations have significant amplitude errors when the broadcaster uses the FMX system.

Stereo separation degradation is shown in Figure 41. The chart shows the percentage of samples where the stereo separation is less than the quantity indicated. For example, stereo separation is less than 30 dB for 60 percent of the receiving lo-

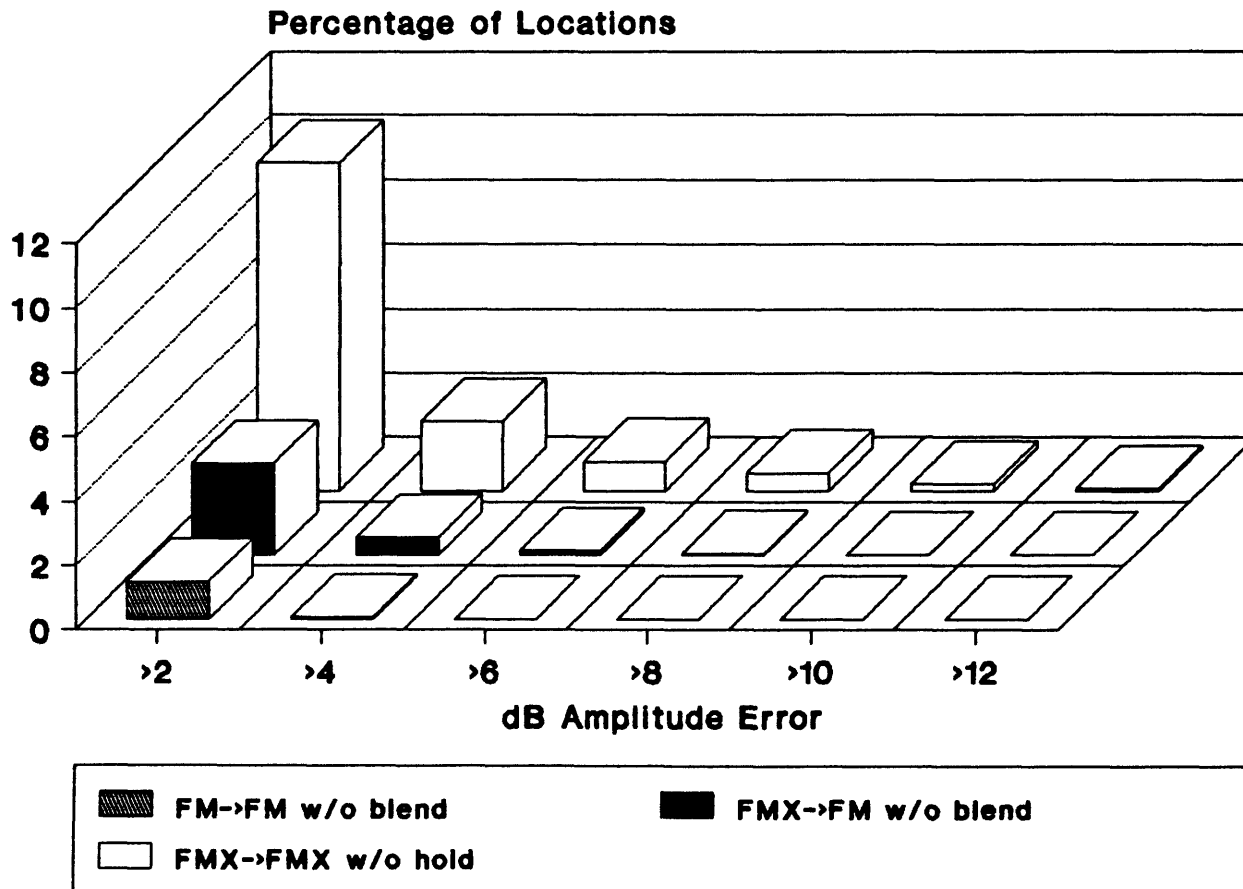


Figure 39: Percentage of receiving locations in all regions having left channel amplitude errors when blend or hold is not used.

cations using an FM stereo broadcast and FM stereo receiver, but is less than 30 dB for 90 percent of the receiving locations when using an FMX broadcast and FMX receiver. Even when using a conventional stereo receiver with an FMX broadcast, stereo separation is degraded in a large number of receiving locations. Note that in each case, more receiving locations have reduced stereo separation when FMX transmission and conventional FM stereo reception is used than when conventional FM stereo transmission and conventional FM stereo reception is used. Further, more receiving locations have reduced stereo separation when FMX transmission and FMX reception is used than when FMX transmission and conventional FM stereo reception is used. Figure 42 shows the data for the case where blend or expander hold is used.

The noise and distortion level (the output of the band reject filter) on the left

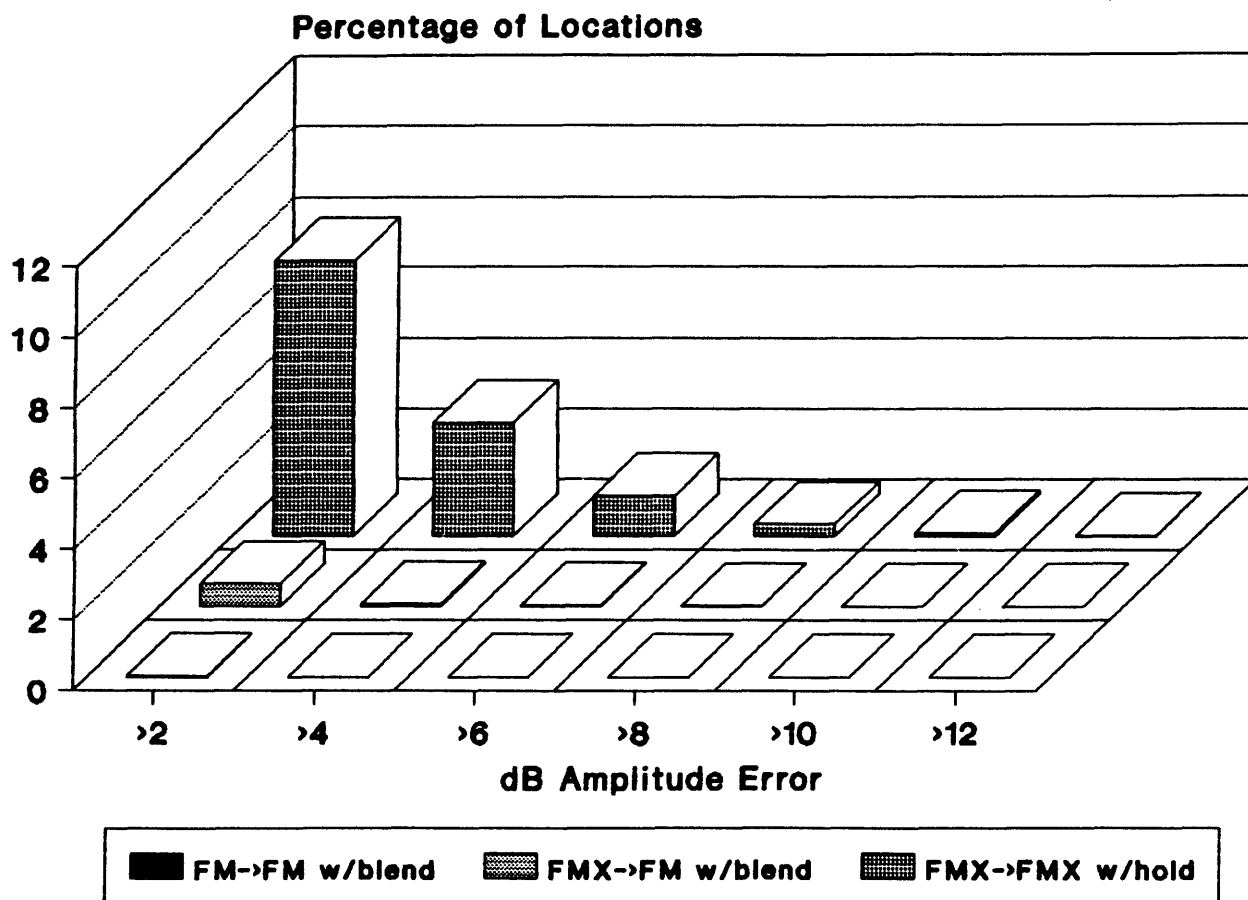


Figure 40: Percentage of receiving locations in all regions having left channel amplitude errors when blend or hold is used.

channel is shown in Fig. 43. The chart shows the percentage of samples where the noise and distortion level exceeds the shown value. The noise and distortion exceeds -40 dB in about 12 percent of the receiving locations with a conventional FM stereo broadcast and FM stereo receiver. However, with an FMX broadcast and FMX receiver, the -40 dB level is exceeded in over 25 percent of the receiving locations. And, with an FMX broadcast and a conventional FM stereo receiver, the -40 dB level is exceeded in 18 percent of the receiving locations. Note that in each case, more receiving locations have increased distortion and noise when FMX transmission and conventional FM stereo reception is used than when conventional FM stereo transmission and conventional FM stereo reception is used. Further, more receiving locations have increased distortion and noise when FMX transmission and FMX re-

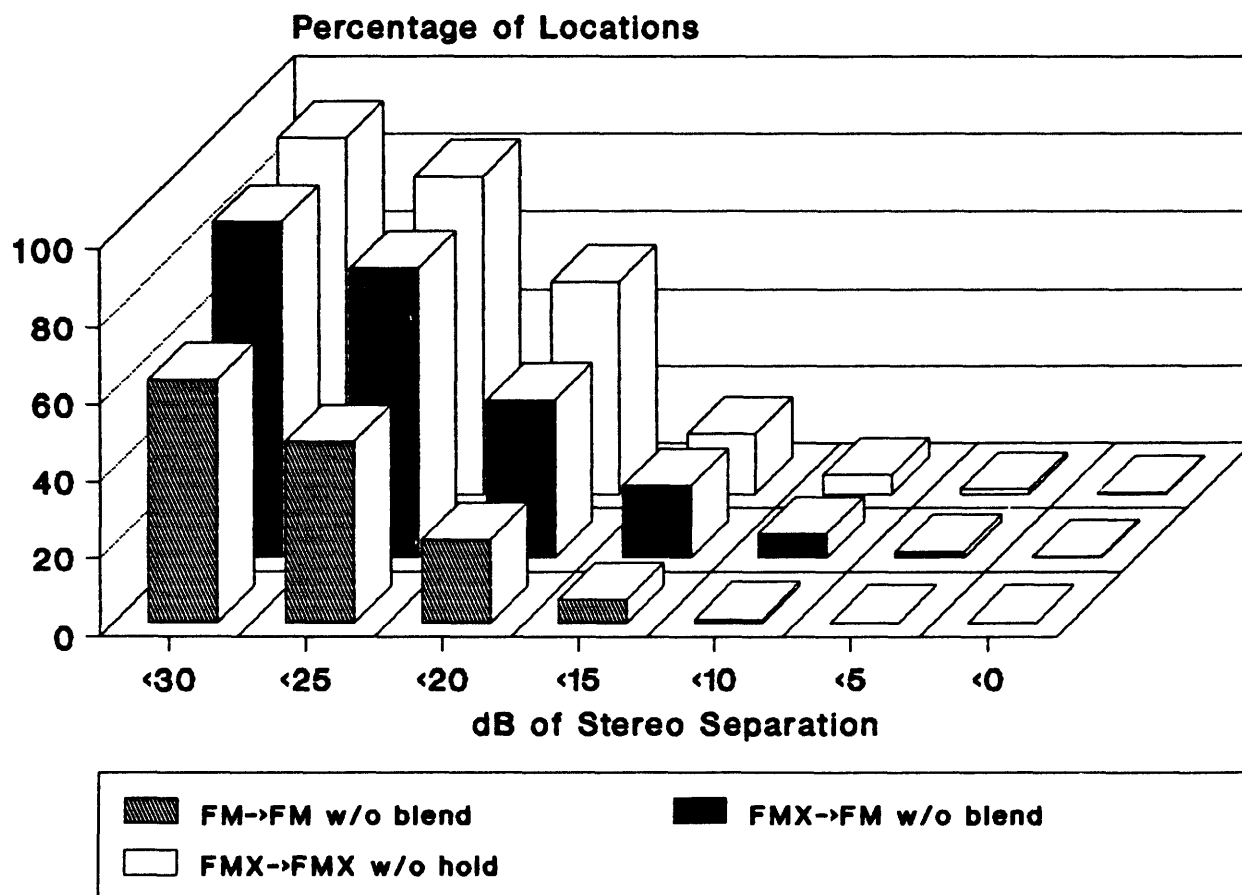


Figure 41: Percentage of receiving locations in all regions having reduced stereo separation when blend or hold is not used.

ception is used than when FMX transmission and conventional FM stereo reception is used. Figure 44 shows the data for the case when blend or expander hold is used.

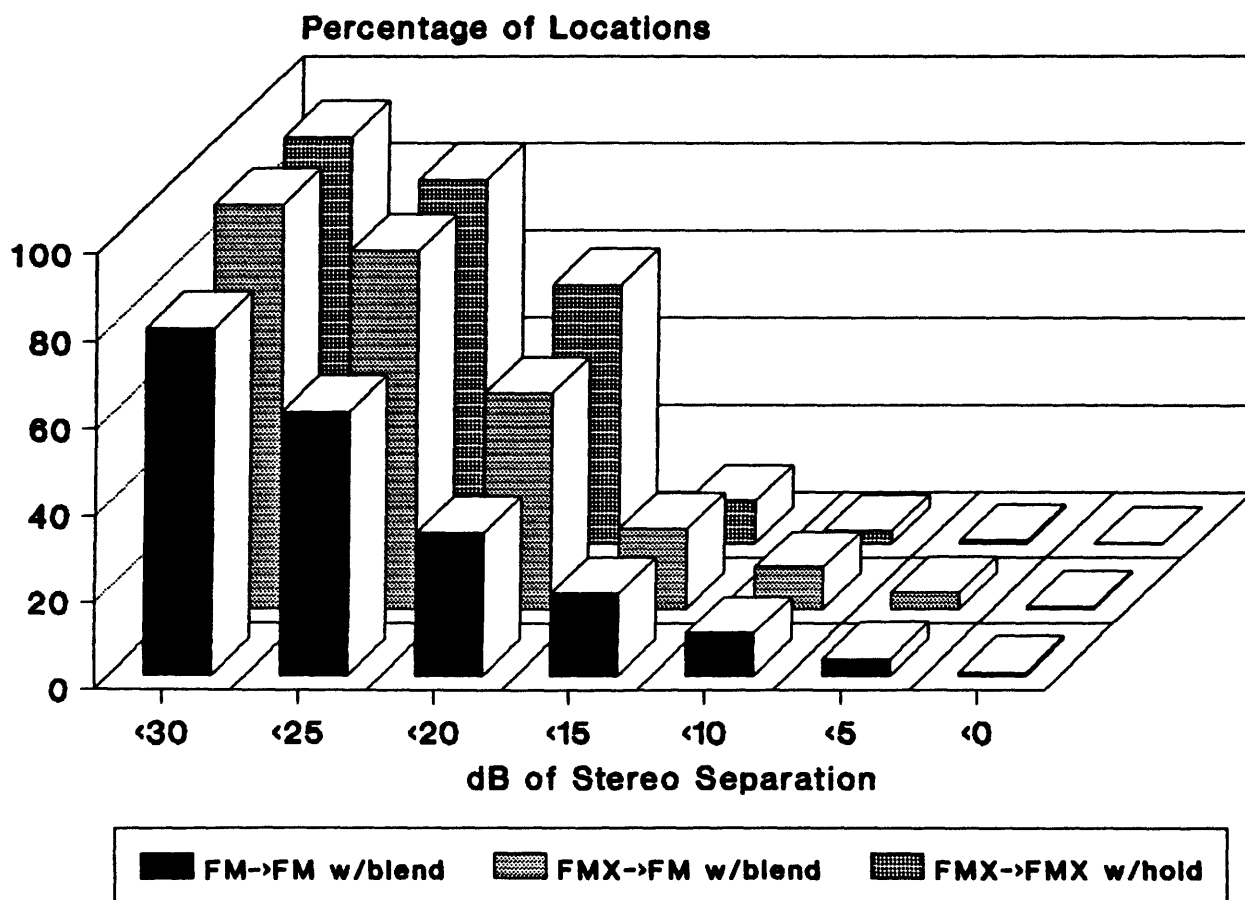


Figure 42: Percentage of receiving locations in all regions having reduced stereo separation when blend or hold is used.

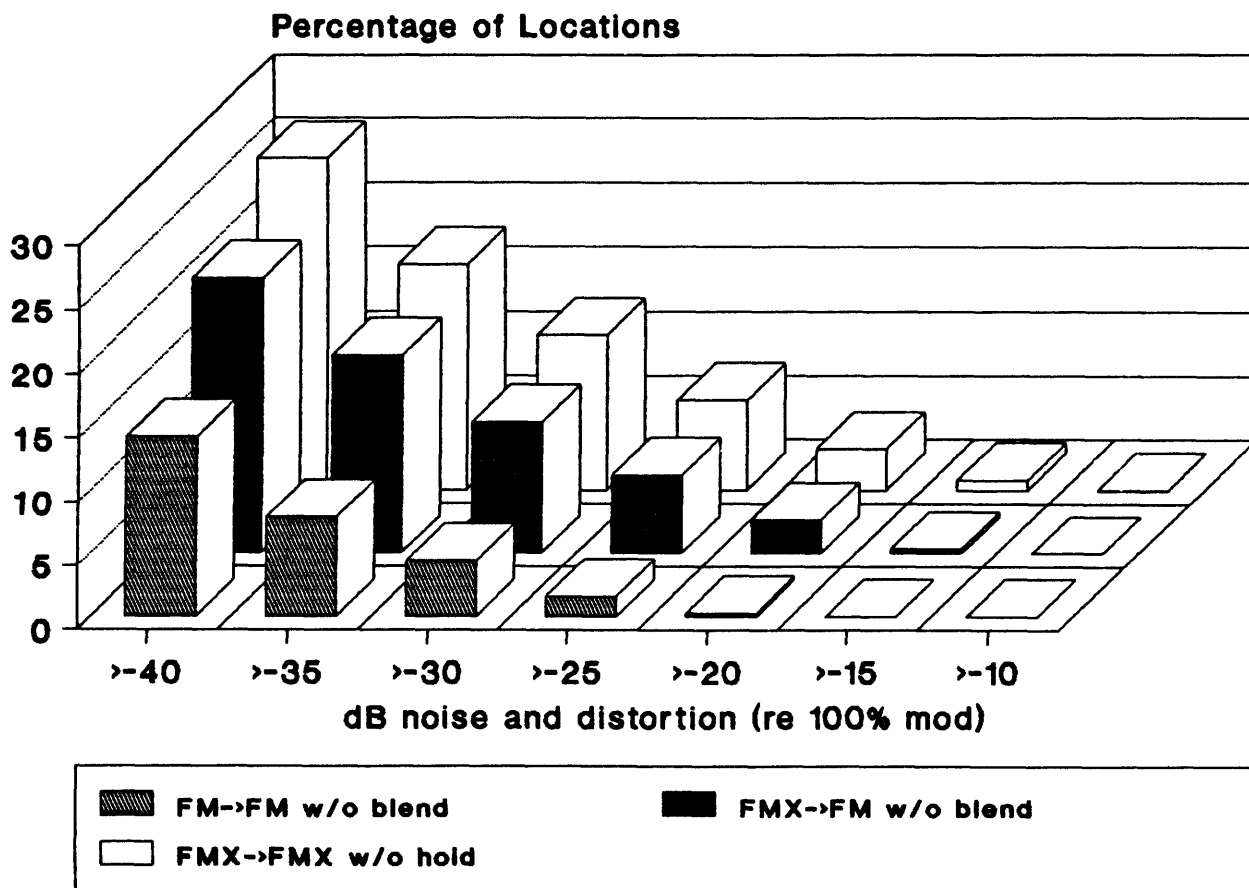


Figure 43: Percentage of receiving locations in all regions with left channel noise and distortion when blend or hold is not used.

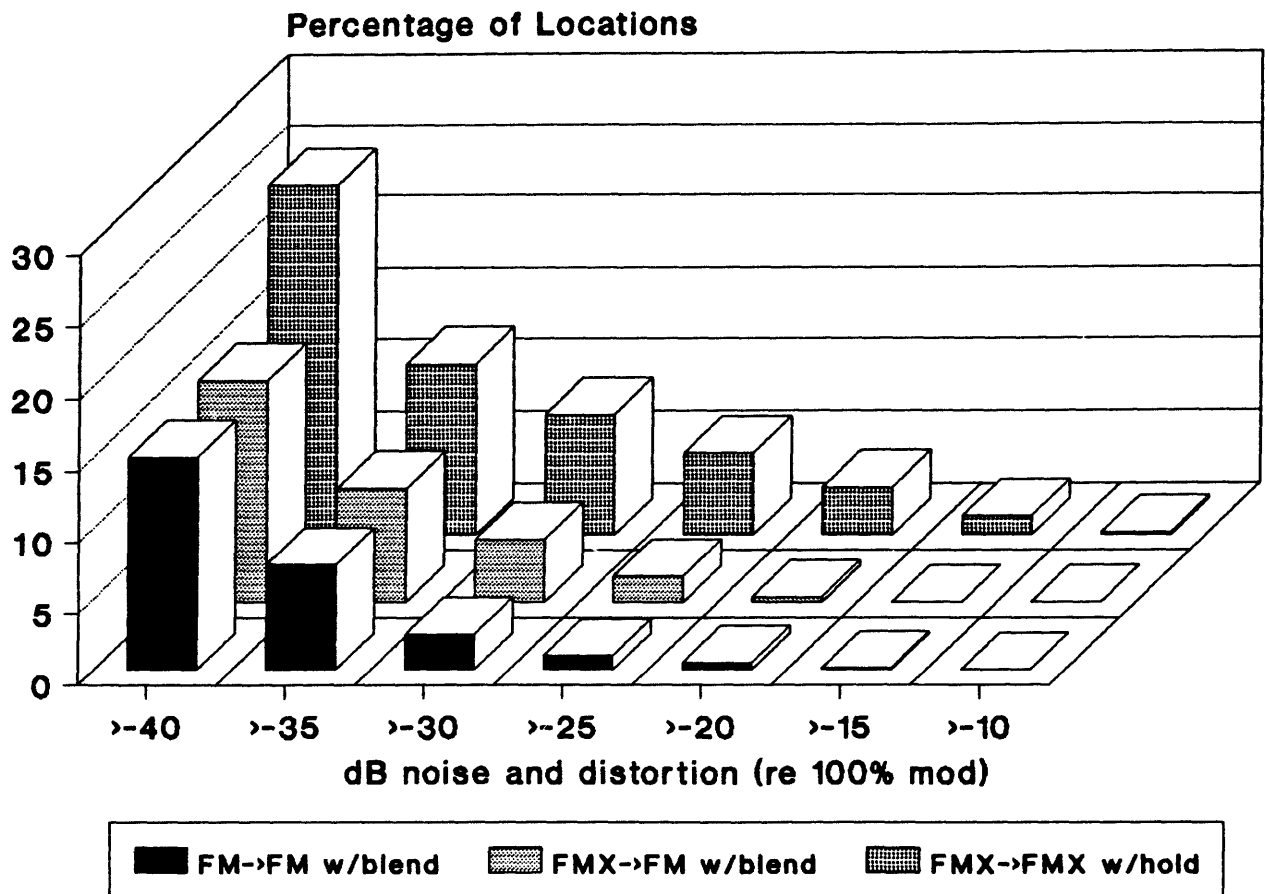


Figure 44: Percentage of receiving locations in all regions with left channel noise and distortion when blend or hold is used.

5.0 Summary

We have developed a mathematical model that can be used to analyze and assess the effects of multipath on any modulation of an FM carrier. The predictions of this model have been verified by simulation and actual field testing.

We have examined two systems of FM transmission that are of current interest – the existing FM stereo system and the proposed FMX system. The results of modelling, simulation, and objective field testing at 15,000 locations lead us inescapably to the following opinions.

1. Broadcast station coverage, instead of being increased as originally hoped, is decreased by the FMX system.
2. FMX transmission degrades reception on existing FM stereo receivers.
3. FMX receivers are inferior to existing FM stereo receivers for receiving FMX transmissions.

The FMX system was originally designed to improve what is, in our opinion, a second order problem of the existing FM stereo system. That problem is the special case of weak signals, without multipath, involving a serious listener, who is sitting in a position to experience the stereo effects and who is playing the music loudly enough such that the background hiss is objectionable. For this special case, the FMX system offers a reduction in the background noise. As we have seen, however, existing FM stereo receivers with automatic blend circuits offer up to twice as much noise reduction on normal FM stereo broadcasts. We believe that increasing blend to further reduce the noise in this special case is a trade-off that many people will find attractive.

The problem, as we see it, is fundamental. The FMX system, in the process of trying to solve a second-order problem with FM stereo, introduced significant artifact into the first-order problem – the multipath problem. This artifact degrades the performance of existing FM stereo receivers when receiving FMX broadcasts. And, the FMX receiver is less capable of dealing with this artifact than is the existing FM stereo receiver when receiving the FMX transmission for which it was designed.

6.0 References

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